Crossbow

XMesh User's Manual

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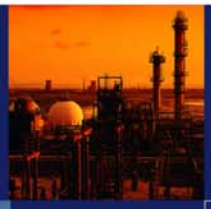

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About This Document

The following annotations have been used to provide additional information.

NOTE

Note provides additional information about the topic.

☑ EXAMPLE

Examples are given throughout the manual to help the reader understand the terminology.

IMPORTANT

This symbol defines items that have significant meaning to the user

⚠ WARNING

The user should pay particular attention to this symbol. It means there is a chance that physical harm could happen to either the person or the equipment.

The following paragraph heading formatting is used in this manual:

1 Heading 1

1.1 Heading 2

1.1.1 Heading 3

This document also uses different body text fonts (listed in Table 0-1) to help you distinguish between names of files, commands to be typed, and output coming from the computer.

Table 0-1. Font types used in this document.

Font Type	Usage
`Courier New Normal`	Sample code and screen output
`Courier New Bold`	Commands to be typed by the user
Times New Roman Italic	TinyOS files names, directory names
Franklin Medium Condensed	Text labels in GUIs

1 Introduction

This manual is intended for developers using Crossbow's *MoteWorks* software platform. User's should have read or be familiar with the following:

- *MoteWorks* Getting Started Guide.
- TinyOS and nesC fundamentals

This chapter gives a general overview of the *XMesh* landscape and features. It includes:

- Mesh Networking Fundamentals
- *XMesh* Overview
- What is a Multi-hop Network?
- *XMesh* Network Landscape
- *XMesh* Features and Benefits

1.1 Mesh Networking Fundamentals

Short-range networks based on wireless mesh networking architectures have evolved to enable power efficient means for managing non-computer devices. Self-organizing mesh network architectures have enabled new wireless machine-to-machine applications, including motion-detection sensors used on the battlefield; thermometers gauging the temperature of food products and pharmaceuticals in transit; and medical devices monitoring patient vital signs.

Wireless sensor networks can be designed in a variety of ways to address different priorities and make the appropriate technology trade-offs based on the requirements of the application. All wireless mesh networking systems share a set of common requirements. These include:

- **Low power consumption** — To support long-term operation, the power consumption of the radio link must be minimized so that devices can be powered by compact, lightweight batteries such as a coin cell battery for long periods of time.
- **Ease of Use** — The network protocol allows the sensor network to initialize itself in a highly ad hoc, self-organizing manner.
- **Scalability** — The network must support the number of nodes required immediately and must also be able to support future growth without causing exponential growth of overhead.
- **Responsiveness** — Topology discover and re-discovery must be efficient, especially for applications where sensor nodes are mobile, such as in mobile machines or equipment or for wearable sensors.
- **Range** — It is more power efficient to emit low strength RF singles to travel a short distance and be relayed a number of times than to transmit higher strength signals for longer range. Repeaters form a network using a protocol that supports multi-hop routing so that data packets can be relayed from one repeater to another when the mobile RF terminal is far away from the base station.

- **Bi-directional communication** — Communication between the gateway and sensor is bi-directional to enable the base station to transmit signals to adjust certain operating parameters in addition to receiving signals transmitting sensor data.
- **Reliability** — While data reliability is always important, it becomes a critical requirement for many applications, for example in medical monitoring.
- **Small module form factor**— A very small form factor for the network modules is needed so that endpoints can fit inside or attach easily to an existing device.

A robust networking protocol is needed to meet the above requirements as well as those of a particular mesh networking design. The networking protocol provides support for the network's topology and manages the routing of data through the network. In order for the application to benefit from the promises of wireless sensor networking, the underlying protocol must support all of these basic requirements.

1.2 Topologies

There are several architectures that can be used to implement wireless sensor network applications, including star, mesh, and star-mesh hybrid. Each topology presents its own set of challenges, advantages, and disadvantages. In order to understand the topologies, you need to be familiar with the components of a wireless sensor network. These components include:

- **Endpoints** — Integrate with sensors and actuators to capture the sensor data. For ZigBee networks these are commonly referred to RFDs (Reduced Functional Devices). RFDs cannot forward network messages upstream or downstream. *XMesh*-ELP Motes behave as RFD devices.
- **Routers** — Extend network area coverage, route around obstacles, and provide backup routes in case of network congestion or device failure. In some cases, routers can also act as endpoints. Routers are also referred to as full-function devices (FFD) in a ZigBee network. All versions of *XMesh*, except *XMesh*-ELP Motes act as FFDs.
- **Gateways** — Aggregate the data from the network, interface to the host, LAN, or the Internet, and act as a portal to monitor performance and configure network parameters.
- **System Software** — provides the networking protocol to enable the self-configuring, self-healing ad hoc network.

Crossbow *XMesh* networks make no distinction between RFDs and FFDs (except for *XMesh*-ELP). All Motes can have integrated sensors and also forward messages upstream and downstream.

Topology refers to the configuration of the hardware components and how the data is transmitted through that configuration. The three most common topologies are star, mesh, and star-mesh hybrid. Each topology presents its own set of challenges, advantages, and disadvantages and each topology is appropriate under some circumstances, but may be unsuitable in others.

1.2.1 Star Topology

A star topology is a single-hop system in which all wireless sensor nodes are within direct communication range — usually 30 to 100 meters — to the gateway. All sensor nodes are identical — they are all endpoints — and the gateway serves to communicate data and

commands to the sensor endpoints. The gateway is also used to transmit data to a higher-level control or monitoring system. The endpoints do not pass data or commands to each others; they use the gateway as a coordination point (Figure 1-1).

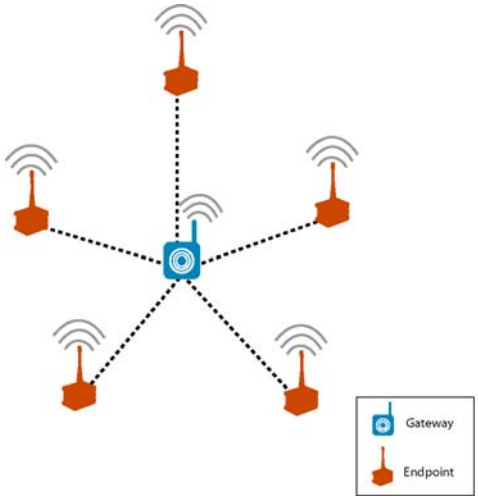


Figure 1-1. Diagram showing a Star Topology

The star topology delivers the lowest overall power consumptions but is limited by the transmission distance of the radio in each endpoint back to the gateway. There are also no alternate communication paths to the endpoints. If path becomes obstructed, communication with the associated endpoint will be lost.

1.2.2 Mesh Topology

Mesh topologies are multi-hopping systems in which all wireless sensor nodes are identical — they are all routers — and communicate with each other to hop data to and from the sensor nodes and the gateway. This is the standard XMesh configuration. Unlike the star architecture, where the nodes can only talk to the gateway, the nodes in a mesh topology can also hop messages among other router nodes (Figure 1-2).

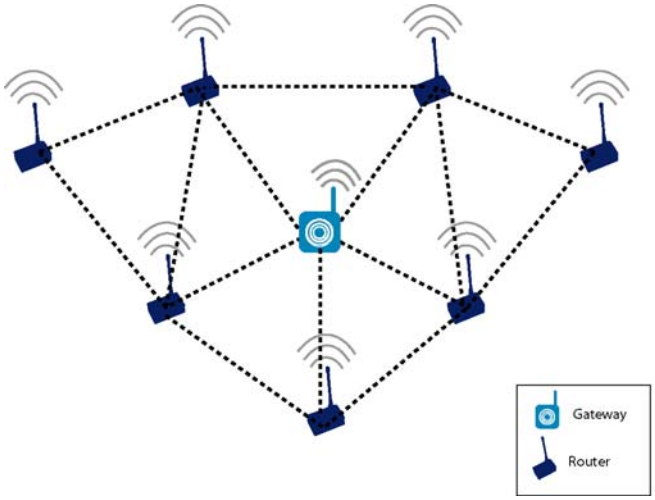


Figure 1-2. Diagram showing a Mesh Topology

The propagation of sensor data through the mesh allows a sensor network to be extended, in theory to an unlimited range. A mesh network is also highly fault tolerant since each sensor node has multiple paths back to the gateway and to other nodes. If a sensor node fails, the network will reconfigure itself around the failed node automatically.

Depending on the number of nodes and the distances between them, the network may also experience increased latency as sensor data is hopped from node to node on its way to the gateway.

1.2.3 Star-Mesh Hybrid

A star-mesh hybrid seeks to take advantage of the low power and simplicity of the star topology, as well as the extended range and self-healing nature of a mesh topology. A star-mesh hybrid organizes sensor nodes in a star topology around routers which, in turn, organize themselves in a mesh network. The routers serve both to extend the range of the network and to provide fault tolerance. Since wireless sensor nodes can communicate with multiple routers, the network reconfigures itself around the remaining routers if one fails or if a radio link experiences interference (Figure 1-3).

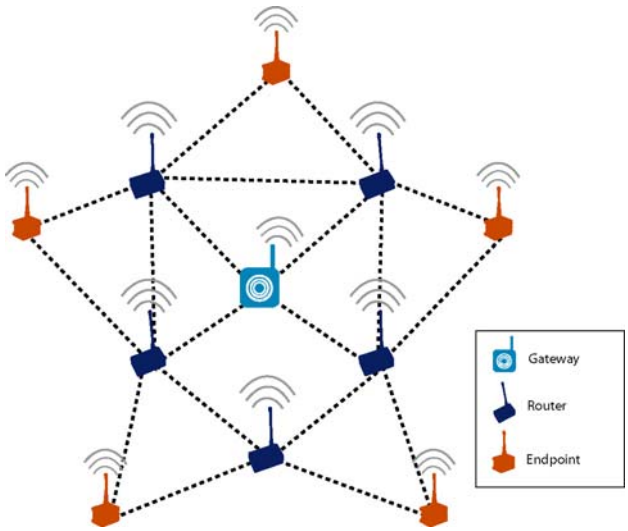


Figure 1-3. Diagram showing a Hybrid Star/Mesh Topology

1.3 XMesh Overview

XMesh is a full featured multi-hop, ad-hoc, mesh networking protocol developed by Crossbow for wireless networks. An *XMesh* network consists of nodes (Motes) that wirelessly communicate to each other and are capable of hopping radio messages to a base station where they are passed to a PC or other client. The hopping effectively extends radio communication range and reduces the power required to transmit messages. By hopping data in this way, *XMesh* can provide two critical benefits: improved radio coverage and improved reliability. Two nodes do not need to be within direct radio range of each other to communicate. A message can be delivered to one or more nodes in-between which will route the data. Likewise, if there is a bad radio link between two nodes, that obstacle can be overcome by rerouting around the area of bad

service. Typically the nodes run in a low power mode, spending most of their time in a sleep state, in order to achieve multi-year battery life.

XMesh is a software library, using the TinyOS operating system that runs on embedded devices called Motes. Motes consist of a:

1. Microprocessor:

   Atmel ATmega128 for MICA2, MICA2DOT and MICAz - ATmega128 has 128K of flash memory, 4K of RAM, and 4K of EEPROM or

   Atmel ATmega1281 for IRIS - ATmega1281 has 128K of flash memory, 8K of RAM, and 4K of EEPROM.

2. Radio: a MICA2 radio at 916/433 MHz or MICAz / IRIS radio at 2.4 GHz.
3. Serial Flash: External flash storage memory to support OTAP (over-the-air programming) and data logging.
4. UID: An integrated circuit that is programmed with a unique 64-bit identifier (for MICA2 and MICA2DOT).

The entire *XMesh* network consists of (see Figure 1-4):

1. One or more Motes which participate in the network
2. A base station node. This is another MICA2 or MICAz mounted on a Crossbow MIB510/520/600 interface board and programmed with *XMeshBase* application. It manages the network and forwards data messages into and out of the mesh.
3. A PC, Stargate or other client which receives data and sends commands into the network.

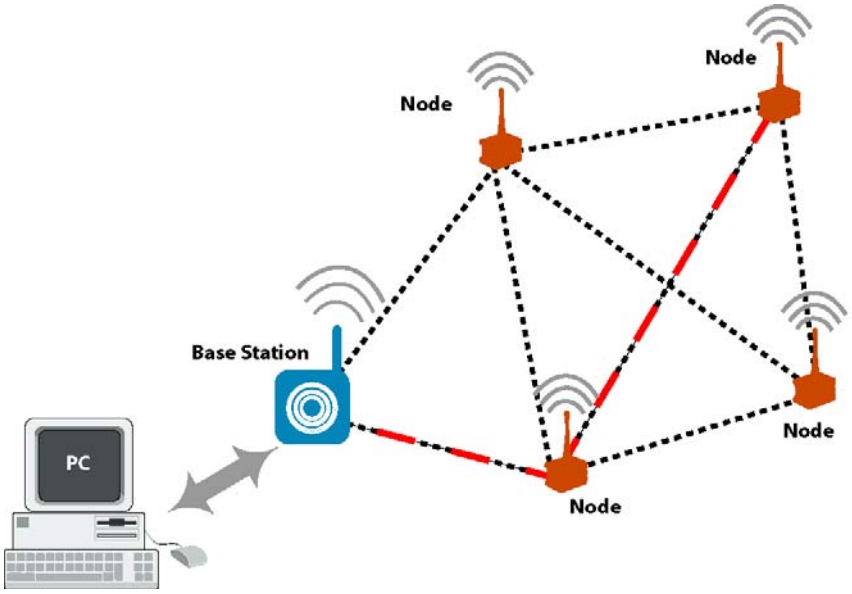


Figure 1-4. XMesh Network Diagram

XMesh provides a TrueMesh networking service that is both self-organizing and self-healing (see TrueMesh section below). *XMesh* can route data from nodes to a base station (upstream) or downstream to individual nodes. It can also broadcast within a single area of coverage or arbitrarily between any two nodes in a cluster. QOS (Quality of Service) is provided by either a

best effort (link level acknowledgement) and guaranteed delivery (end-to-end acknowledgement). Also, *XMesh* can be configured into various power modes including HP (high power), LP (low power), and ELP (extended low power).

The *XMesh* networking protocol has various options including low-power listening, time synchronization, sleep modes, any-to-base and base-to-any routing. All Crossbow sensor and data acquisition boards that can make up a wireless sensor network are supported with *XMesh* enabled applications.

The *XMesh* network has the following features:

- MICA2, MICA2DOT, and MICAz support.
- Low power (typically less than 220 µA average current (without sensor board).
- Network time synchronization to ± 1 msec.
- Low power listening with an 8 times per second wake-up interval, allowing for rapid message transfer across the network. The default sampling period is 3 minutes, although many other sampling intervals are allowed.

The *XMesh* network has been extensively tested both at indoor and outdoor locations. In a typical indoor test, nodes are placed at every 300 sq ft. to cover a 10,000 sq ft facility. To simulate larger distance between nodes, the radio transmit power was turned down to -6dBm. In outdoor tests, nodes are spread across several acres of rugged terrain with an average density of one Mote per 10,000 sq ft and at full radio power. Statistical analysis across many deployments shows on average greater than 90% of all traffic generated at any node will be collected at the base station without the use of end-to-end acknowledgements (guaranteed delivery).

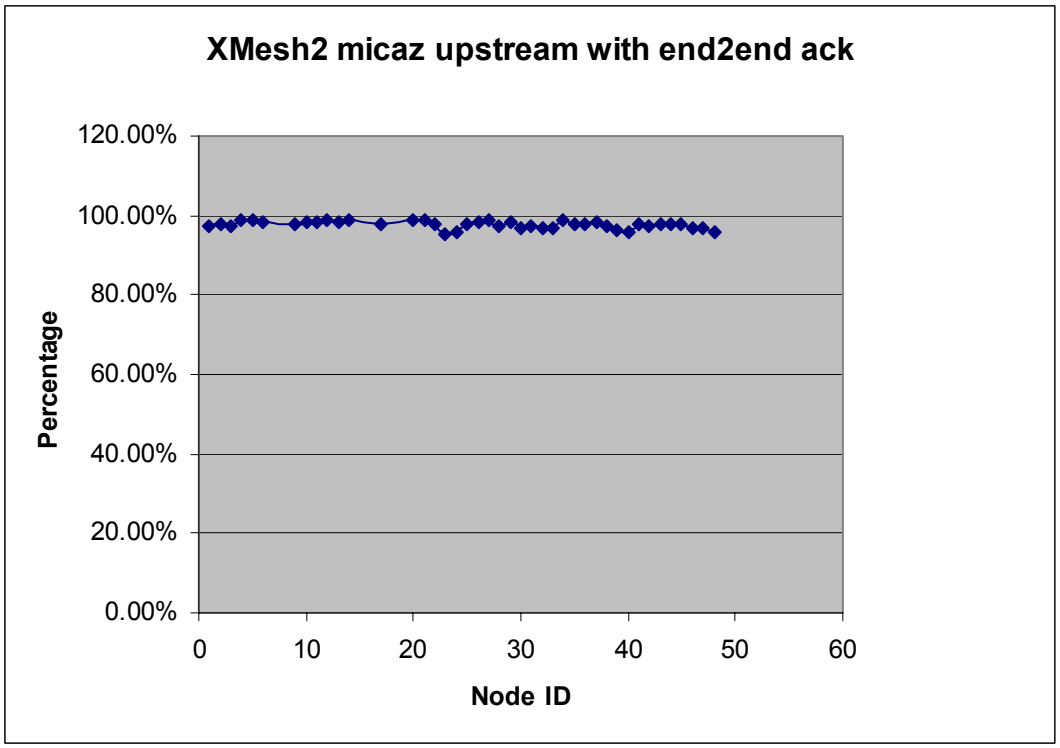


Figure 1-5. Percent Packet Delivery for 48 Mote, 72 Hour Test

1.4 *XMesh* Network Landscape

A wireless network deployment is composed of the three distinct software tiers:

1. The **Mote Tier**, where *XMesh* resides, is the software that runs on the cloud of sensor nodes forming a mesh network. The *XMesh* software provides the networking algorithms required to form a reliable communication backbone that connects all the nodes within the mesh cloud to the server.
2. The **Server Tier** is an always-on facility that handles translation and buffering of data coming from the wireless network and provides the bridge between the wireless Motes and the internet clients. *XServe* and *XOtap* are server tier applications that can run on a PC or Stargate. (Refer to *XServe* User's manual)
3. The **Client Tier** provides the user visualization software and graphical interface for managing the network. Crossbow provides free client software called *MoteView*, but *XMesh* can be interfaced to custom client software as well.

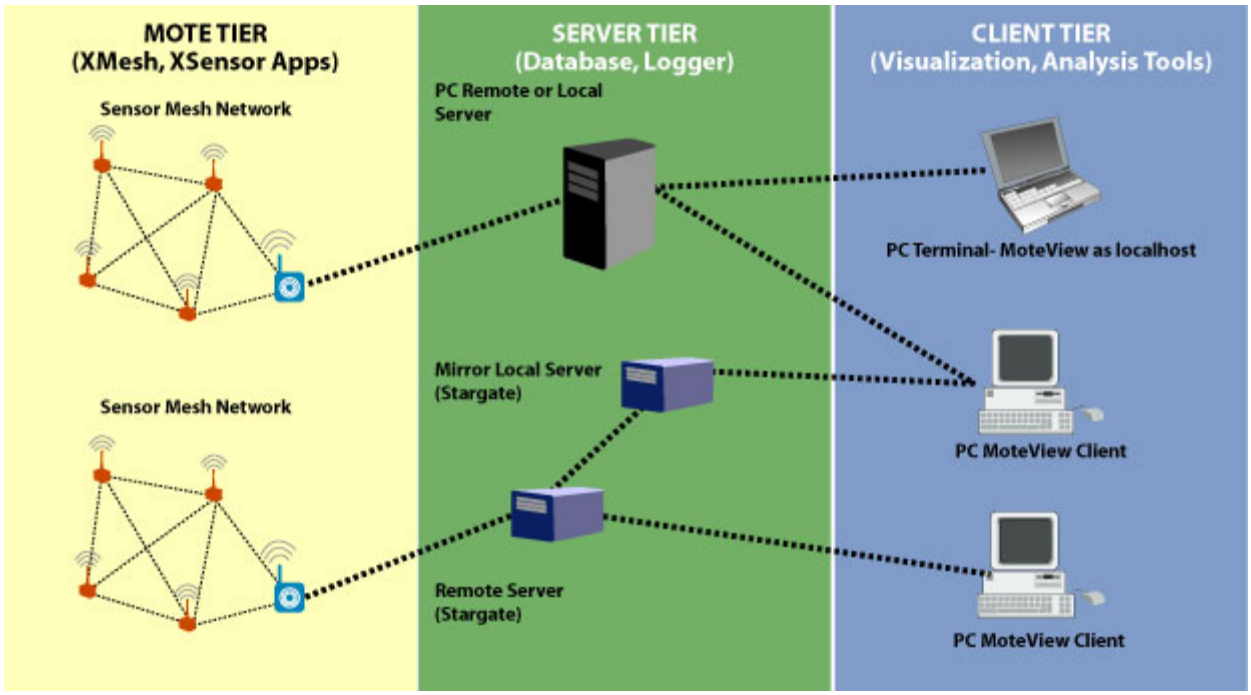


Figure 1-6. Software Framework for a Wireless Sensor Network

An *XMesh* sensor network system consists of multiple motes (MICA2/MICAz) and a base station unit (MICA2/MICAz) installed on an interface board (eg. MIB520). This base station Mote serves two purposes:

1. It acts as the Gateway between the Mote Tier and Server Tier. The base station communicates with other motes over the radio, and with the server using serial communication. In this way, the base station forms a bridge to send and receive messages between a host system (PC and/or Stargate) and the rest of the mesh network.
2. It forms the network and directs all data messages from the Motes to itself. To other Motes in the network, this base station Mote can forward messages to the PC (host) with

zero energy cost. The base station Mote is always identified as "node 0" in a single base station system.

In addition to the base station, the mesh network consists of some number (1-100s) of other Motes, each with a unique node identification number. This system of Motes, running *XMesh*, will self-configure itself into a network and route radio messages upstream (from Motes to the base station) and downstream (base to Motes).

1.5 *XMesh* Features and Benefits

XMesh has many features and benefits. They include:

- TrueMesh
- Mutliple Transport Services
- Multiple Quality of Service (QoS) Modes
- Multiple Power Modes
- Health Diagnostics
- Time Synchronization
- Over-the-Air-Programming (OTAP)

1.5.1 TrueMesh

TrueMesh technology refers to the ability of the nodes to dynamically seek new routes for delivering packets when parts of the network go offline due to radio interference or power duty-cycling. A network may be formed ad-hoc by simply scattering a collection of nodes next to each other. The nodes will discover each other and build a routing tree based on the link estimates of the particular radio environment that they belong to. Therefore, nodes within an *XMesh* network are truly self-organizing and self-healing.

1.5.2 Multiple Transport Services

XMesh provides multiple transport services for communication between nodes. They are:

- Upstream – Delivers packets from a node to the base station Mote.
- Downstream – Delivers packets from base station Mote to node(s)
- Single Hop – Delivers packets to neighboring nodes only.

1.5.3 Multiple Quality of Service (QoS) Modes

XMesh provides multiple qualities of service modes. They are:

- Best Effort – Link level acknowledgement where motes will try multiple times to transmit a message to its immediate neighbor.
- Guaranteed Delivery – Provides end-to-end acknowledgement where a message is transmitted through the mesh to the base station (or downstream) and an acknowledge message is then sent back to the originator.

1.5.4 Multiple Power Modes

XMesh can be configured to run in one of the several power modes. The modes are:

1. **High Power (HP)** – The HP mode provides:
   - TrueMesh capability
   - Every node in the network can route data
   - High bandwidth, low latency (full channel utilization)
   - Mote radios are always powered.
2. **Low Power (LP)** – The LP mode provides:
   - TrueMesh capability
   - Every node in the network can route data
   - Low bandwidth, high latency (ideal for low data rate applications)
   - Mote radios are normally in a low power sleep state and wake periodically to check for radio traffic.
3. **Extended Low Power (ELP)** – The ELP mode provides:
   - Used only for end nodes of the network
   - Nodes cannot route data
   - Uses hybrid star mesh configuration

1.5.5 Health Diagnostics

Within the *XMesh* network, nodes can automatically transmit health information to the base station. The health information includes data on how well the node is performing in the network with regards to radio traffic, battery voltage, and parent's node Radio Signal Strength Indicator (RSSI). The base station Mote will forward the health information data to *MoteView (*Refer to *MoteView* User's manual*)* and *XSniffer* to monitor and diagnose the health of *XMesh*.

1.5.6 Time Synchronization

XMesh-LP support a network global time synchronization to ±1 msec. The time stamping is used to synchronize radio messages but is also available to users to synchronize sensor measurements.

1.5.7 OTAP

XMesh supports Over-the-Air-Programming which allows users to reprogram all nodes in the mesh with new code. OTAP uses a directed downstream strategy that allows different code images to be sent to different Motes. This allows users to deploy networks of multiple sensor boards and only reprogram the units of interest. OTAP also uses a promiscuous listening mode; motes that can overhear the new code download, and know that they also need the same image, will store the code transmissions.

2 Building *XMesh*

This chapter guides the user through building *XMesh* and deploying a small network. It includes:

- The *XMesh* build environment.
- Building an *XMesh* application.
- Deploying and testing a small network.
- Using binaries to build an application.
- Accessing the Crossbow CVS code repository

2.1 XMesh Build Environment

XMesh is compiled and built using *MoteWorks* (refer to *MoteWorks* Getting Started Guide). For building *XMesh* applications the important parameters are located in 3 files.

- *MakeXbowlocal*
- *Makefile*
- *Makefile.component*

When building any application it is necessary to set the correct parameters in each of these files.

2.1.1 MakeXbowlocal

The *MakeXbowlocal* file contains global parameters which are applicable across all applications built for a particular installation. The file is located in ***/MoteWorks/apps***.

Table 2-1. *MakeXbowlocal* Parameters

Parameter	Description
RADIO_CLASS	This parameter defines the radio band in which the network communicates for MICA2/MICA2DOT radios. The operating band is defined by the mote's radio hardware. This should correspond to the label on the board. The available classes for Mica2 and Mica2Dot are 916 MHz, 433 MHz and 315 MHz.
RADIO_CHANNEL	This parameter defines the radio channel the network is operating on. Each band has multiple channels upon which it can operate. The user should choose a channel which is not being used by other wireless devices in the network (including other sensor networks). See table below for MICAz settings.
RADIO_POWER	This parameter defines the power level for the radio.
DEFAULT_LOCAL_GROUP	The local group is the group id upon which each node in your network will communicate on. The group id is a way for multiple networks to operate on the same radio band and channel yet filter communication by group id.

The Table 2-2 shows the available radio channels for the MICAZ 802.15.4 radio. USA/FCC & Canada regions have 27 total channels allocated. Channels 11 to 26 are in the 2.4 GHz band.

Table 2-2. IEEE 802.15.4 Channels. All frequencies are in GHz.

Channel	Lower Frequency	Central Frequency	Upper Frequency
11	2.404	2.405	2.406
12	2.409	2.410	2.411
13	2.414	2.415	2.416
14	2.419	2.420	2.421
15	2.424	2.425	2.426
16	2.429	2.430	2.431
17	2.434	2.435	2.436
18	2.439	2.440	2.441
19	2.444	2.445	2.446
20	2.449	2.450	2.451
21	2.454	2.455	2.456
22	2.459	2.460	2.461
23	2.649	2.650	2.651
24	2.469	2.470	2.471
25	2.474	2.475	2.476
26	2.479	2.480	2.481

2.1.2 Makefile

The *Makefile* contains build specific parameters. Most importantly it defines high level services which should be included for the particular application by way of a list of goals. The file is located in ***/MoteWorks/apps/<specific app name>***/. An example *Makefile* is

Users can either edit the *Makefile* for these parameters or include them in the command line. The command line will override any parameters set in the *Makefile*.

☑ EXAMPLE

- To force *XMesh-HP* for a MICAz:

  `make micaz route,hp`

- To force a base station build for a MICAz and *XMesh-HP* :

  `make micaz base route,hp`

An example of a *Makefile* is:

```
include Makefile.component
include ../../../MakeXbowlocal
# Automatically add certain command-line goals:
GOALS += basic freq route,hp
```

Table 2-3. *Makefile* Services

Service	Description
`basic`	Responsible for including the standard Crossbow services. This service should be included in all *XMesh* applications.
`freq`	Sets the radio channel for the application. This feature acts as an application specific override of the `RADIO_CHANNEL` parameter set in the *MakeXbowlocal* file. Usage is: `freq,<freq>` or `freq,<channel #>`
`group`	Sets the group id for the application and acts as an override of the `DEFAULT_LOCAL_GROUP` parameter set in the *MakeXbowlocal* file. Usage is: group,<group #>.
`power`	Sets the radio power and acts as an override of the `RADIO_POWER` parameter set in the *MakeXbowlocal* file. Usage is: `power,<power #>`.
`route`	Sets the *XMesh* power operating mode. Usage is: route,<operating mode>. The available operating modes are: • `hp` to build *XMesh* high power. • `lp` to build *XMesh* low power. This will build the time synchronized MICA2 mesh or asynchronous MICAZ mesh. • `elp` to build *XMesh* extended low power
`base`	The base goal sets the application image as the base station node in *XMesh*. This should only be used for building *XMeshBase*.

2.1.3 Makefile.component

The *Makefile.component* contains application specific parameters. The parameters defined in the component file are applicable to the particular application and are provided by the application itself.

Table 2-4. *Makefile.component* parameters

Parameter	Description
`COMPONENT`	The component parameter tells the build system which application is being made and also can include #defines to configure *XMesh*. The component listed here should be the top level application component in the application

☑ EXAMPLE

```
COMPONENT=ELPTest
SENSORBOARD=micasb
INCLUDES+= -I../../../../tos/lib/XMesh2_TestSuite
#DEFINES += -DROUTE_UPDATE_INTERVAL=15000
#DEFINES += -DTOSH_DATA_LENGTH=50
DEFINES += -DDATA_REPORT_RATE=10
```

2.2 Building an *XMesh* Application

In this section we will build a simple *XMesh-HP* application to demonstrate building a multihop network. The application we will develop is the `XMeshCountToLeds` application. In this application each node in the network will increment its individual count every one second and

send the value back the base station for viewing. To verify that the count application is working the LEDs will display the count value.

To build this application we will need the following equipment:

- **Motes:** At least 3 motes running under similar radio platforms, for example the MICA2 and MICA2DOT or the MICAz platform.
- **Mote Programming Board:** You will need a programming board to program the motes and to act as an interface between your PC and the mote network. Potential programming boards are the MIB510, MIB520, or MIB600. You will also need the accompanying cabling to connect the board to your computer (serial for MIB510, USB for MIB520 and Ethernet for MIB600).
- **Personal Computer:** You will need a PC running Linux or Windows installed with Cygwin.
- **Crossbow MoteWorks Installation CD:** The *MoteWorks* installation CD comes with necessary PC side software to build, install, and analyze Mote networks.

Before building and installing the example application we will give a brief overview of the application itself.

IMPORTANT: The following assumes knowledge of TinyOS/nesC programming. Please refer to *MoteWorks* Getting Started Guide for more information on TinyOS and nesC programming.

Refer to Appendix C to check that the correct TinyOS environment variables are set.

The *XMeshCountToLeds* application is located in ***MoteWorks/apps/examples/XMeshCountToLeds***.

The application is composed of two main files:

- *XMeshCountToLeds.nc*: Contains component wiring information and shows how the application connects to the *XMesh* multihop networking service.
- *XMeshCountToLedsM.nc* : Contains the application

The *XMeshCountToLedsM.nc* file increments a count variable every second and displays the count value in binary on the LEDs. The application then sends the count variable along with the node id to the base station for viewing.

XMesh provides a rich set of services to send and receive application messages (see Chapter 5). In this example we will display the basic UPSTREAM send service. The service implemented in this application will have no reliability guarantees and runs at full power.

Below are code excerpts from *XMeshCountToLedsM.nc*:

```
void displayCount(uint16_t value){
  if (value & 1) call Leds.redOn();
  else call Leds.redOff();
  if (value & 2) call Leds.greenOn();
  else call Leds.greenOff();
  if (value & 4) call Leds.yellowOn();
```

```
    else call Leds.yellowOff();
  }
event result_t Timer.fired(){
        g_count++;
        displayCount(g_count);
        post sendMsg();
        return SUCCESS;
  }
```

The application runs a one second timer which increments a count variable on every fire. The count variable is then displayed using the LEDs. The number is displayed as a 3 bit binary number with the yellow led being most significant bit and the red led being the least significant bit.

Once we have displayed the count value to the LEDs the application attempts to send the count value and node id to the base station PC using the *XMesh* multihop network. As described above, this application will only send UPSTREAM messages with no reliability guarantees.

Below is a code excerpt from the *XMeshCountToLeds.nc* :

```
implementation{
  components
  Main,XMeshCountToLedsM,LedsC,TimerC,XMeshRouter;
  StdControl = XMeshCountToLedsM.StdControl;
  Main.StdControl -> TimerC.StdControl;
  Main.StdControl -> XMeshRouter.StdControl;
  Main.StdControl -> XMeshCountToLedsM.StdControl;
  XMeshCountToLedsM.Leds -> LedsC.Leds;
  XMeshCountToLedsM.Timer -> TimerC.Timer[unique("Timer")];
  XMeshCountToLedsM.MhopSend -> XMeshRouter.MhopSend[10];
}
```

The *XMesh* service is implemented by the `XMeshRouter` component. The routing component provides a sending interface in `MhopSend` which sends packets into the network. A receiving interface is also implemented but will be described later. Each application which links into the *XMesh* send interface attaches with its own application id. *XMesh* uses this application id to multiplex packets from different applications in the network. In this example we chose application id 10 to interface with *XMesh*. The id value is important, in that each application on *XMesh* should have a unique id and both the send and receive interface for an application should use the same id.

Below are code excerpts from the `XMeshCountToLeds` application for sending multihop messages.

```
TOSMsg g_msg;
task void sendMsg(){
      uint16_t bufferLength = 0;
       CountMsg_t* countMsg = (CountMsg_t*)
```

```
        MhopSend.getBuffer(&g_msg,&bufferLength);
        countMsg->nodeId = TOS_LOCAL_ADDRESS;
        countMsg->nodeCount = g_count;
        call MhopSend.send(
          BASE_STATION_ADDRESS,
          MODE_UPSTREAM,&g_msg, sizeof(CountMsg_t));
}
```

The basic messaging structure in TinyOS is the `TOSMsg` object. The application declares a `TOSMsg` which it will fill with application specific messaging information. In this case the information is the local node id and the current count value. Though the message object is owned by the application, *XMesh* will fill out the initial portion of the message with its own mesh information. To retrieve the area of message buffer that is for use by the application the code uses the `MhopSend.getBuffer()` method. The method returns a pointer to the location in the buffer where the application can insert its information.

Once the packet is filled out the application must hand the message to *XMesh* to send. The `MhopSend.send()` method provides the sending interface. The application provides the address of the receiver, in this case the `BASE_STATION_ADDRESS`. It also provides the send mode. In this application we are using the UPSTREAM mode with no reliability guarantees as shown by the parameter MODE_UPSTREAM. After *XMesh* has attempted send the message it informs the application of the result through the `MhopSend.sendDone()` event.

An example of the *MakeXbowlocal* file for this application could have parameters shown in Table 2-5.

Table 2-5. *MakeXbowlocal* Parameters

Parameters	MICA2 / MPR600	MICAz / MPR2600	IRIS / M2110
RADIO_CLASS	916	N/A	N/A
RADIO_CHANNEL	10	13	11
RADIO_POWER	0xff	TXPOWER_0DBM	TXPOWER_3_2DBM
DEFAULT_LOCAL_GROUP	0x3	0x3	0x3

An example of the *Makefile* for this application could be:

```
# $Id: Makefile,v 1.2 2005/11/03 21:56:20 rkapur Exp $
include Makefile.component
include ../../MakeXbowlocal
# Automatically add certain command-line goals:
GOALS += basic freq route,hp
TOSMAKE_PATH = ${TOSROOT}/contrib/xbow/tools/make
include ${TOSROOT}/tools/make/Makerules
```

The *Makefile.component* for this application is:

```
COMPONENT=XMeshCountToLeds
MSG_SIZE = 49
```

Once all the correct parameters are set for an application the build process can be started by executing the make command from the application directory. The make command has the following parameters:

make <mote platform> binlink,none (build from source code)

make <mote platform> hp (build from XMesh/Radio binaries)

The <mote platform> corresponds to the hardware platform:

mica2

mica2dot

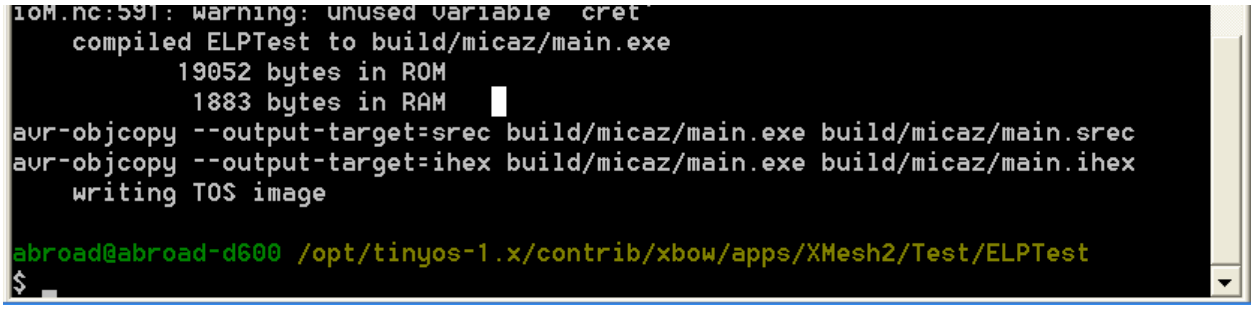
micaz

iris

IMPORTANT: If the default ROUTE_UPDATE_INTERVAL has been changed make sure the *Makefile.Component* for both the application and *XMeshBase* are the same for this parameter.

At the end of the build the code space (ROM) and variable storage memory (RAM) allocation of the application will be displayed (see below). It is important to make sure that the application does not consume too much RAM otherwise there may not be enough space for the stack and the code can crash.

When using the ATmega128 there are 4096 bytes of RAM. The maximum RAM usage should not exceed 3750 bytes.



Once the application has been built the motes can be programmed. To install an application to the mote users need a programming board connected to their computer. Available programming boards and their connections are:

- MIB510 with serial connection
- MIB520 with USB connection
- MIB600 with Ethernet connection

To install an application onto the mote, attach it to the programming board and connect the programming board to the PC. Once connected, program the mote using the GNU make system.

```
make <mote platform> install,<node_id> mib510|mib510|mib600, <device
location>
```

The <mote platform> is defined above. The <node id> parameter is the node id you wish to assign. The value zero is reserved for the base station. Finally you specify the type of programming board connected to the mote and the location of the device. The <device location> is determined by your operating system and whether you have a USB or serial connection.

The ATmega128's internal fuses must also be correctly set. This can be done using the uisp.exe in the application directory or the fuses script. Refer to Appendix B for the correct fuse settings. For *XMesh-HP* the default fuse setting are used. For *XMesh-LP* the JTAG fuse must be disabled and the internal oscillator enabled.

⚠ **WARNING:** The correct ATmega128 fuses must be set. Refer to Appendix B.

Programming the base station (Refer to Chapter 9)

Compile and program a Mote (as Mote address 0) with the application in ***/MoteWorks/apps/XMesh/XMeshBase*** as

```
make <mote platform> base route,hp
```

Programming a Sniffer Mote (Refer to Chapter 11)

Compile and program a sniffer Mote with the application in ***/MoteWorks/apps/general/XSniffer***

```
make <mote platform>
```

2.3 Deploying the Network

Once the motes are deployed and powered use *XSniffer* to monitor the network activity (refer to Section 11.2). This allows users to monitor the mesh formation, route update packets, and all upstream and downstream traffic. After you have seen the routing packets being exchanged using *XSniffer*, you are able to view the individual packets arriving through the base station. Using *XServe* or a standard terminal program (e.g. HyperTerminal), you can view the raw data packets coming from the base station. Refer to Chapter 9 for more information on the serial data packets.

The screen shot in Figure 2-1 shows the mesh formation of a single Mote:

1. The initial transmissions from the mote are all broadcast (bcast) transmissions since the mote has not yet joined the mesh. This occurs until the 1.11.24.190 time.
2. At 1.11.19.904 the base station transmits a route update message. The message tells the mote that the base station can hear it.
3. At 1.11.24.060 the mote transmits a route update message telling the base that the mote can hear it.
4. At 1.11.24.190 the mote has joined the mesh and now directs its messages directly to the base.

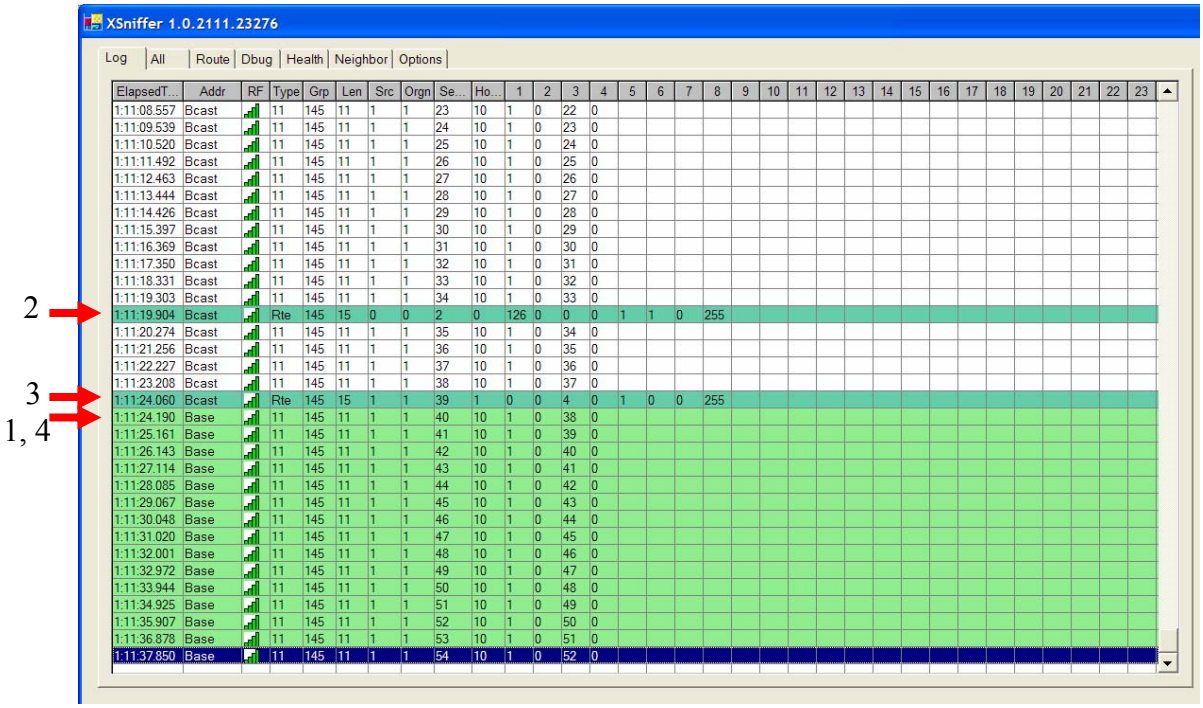


Figure 2-1. Screenshot displaying *XSniffer* Output

2.4 Using Binaries

Crossbow provides *XMesh* in the form of binary components which allow users to link to *XMesh* object files and use services provided therein. The default make commands will use these binaries. For example:

```
make micaz route,hp
```

builds the MICAz high power mesh using the binaries files.

The XMesh binaries are located ***/Moteworks/tos/lib/XMeshBin***

3 Hardware Overview

This section gives a general overview of:

- MICAz and MICA2 hardware platforms.
- ATmega128 resources
- Using ATmega128 resources
- Low power operation
- Optimizing for battery operation
- Hardware debugging techniques

3.1 Hardware Platforms

The table below summarizes the core elements of the MICAz, MICA2 and IRIS hardware platforms:

Table 3-1. Hardware Platform Summary

Platform	MICAz	MICA2	IRIS
Microprocessor	ATmega128L	ATmega128L	ATmega1281
Radio	CC2420 (2.4GHz)	CC1000 (433MHz,916MHz)	RF230 (2.4GHz)
External Serial Flash	AT45DB041 512 Kbytes The serial flash can be used for over-the-air-programming (OTAP) and/or data logging		
Unique ID (integrated circuit)	DS2401P 64-bit This chip contains a unique 64 bit identifier.		
51-Pin Connector	Yes, except for OEM modules This connector brings out most of the ATmega128L signal		

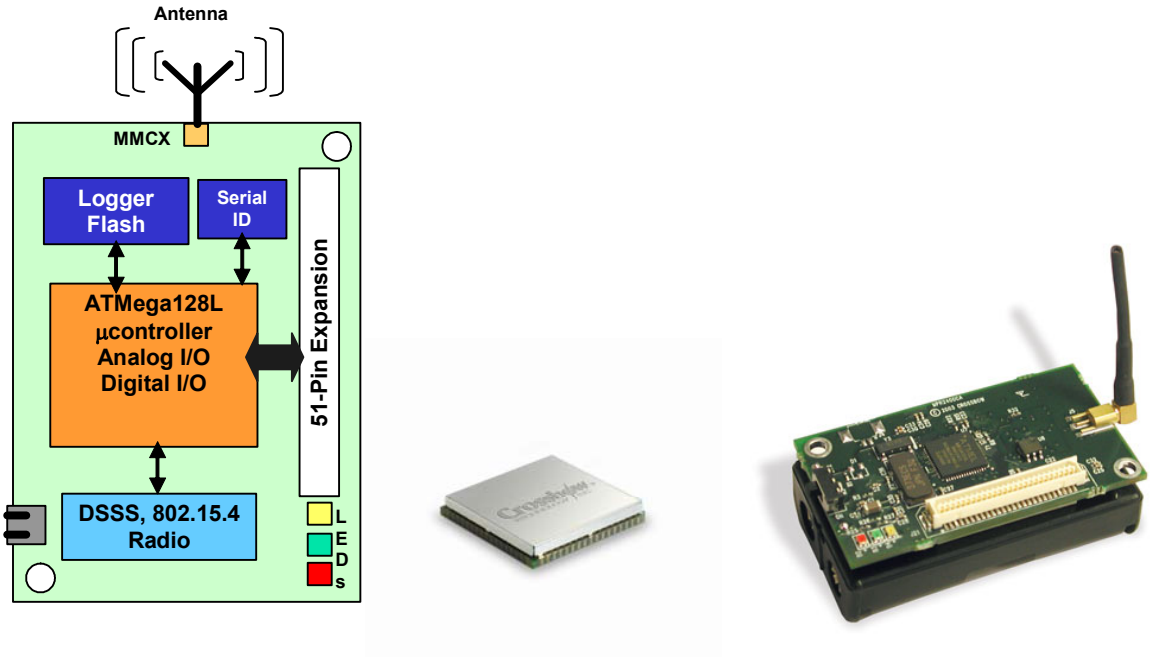


Figure 3-1. The MICAz Hardware Architecture

The Table 3-2 shows the 51-pin expansion connector for the MICAz / IRIS and the pins that are available for user application.

Table 3-2. MICAz/ IRIS 51-pin Connector Interface

Pin	Name	Description	Pin	Name	Description
1	GND	Ground	27†	UART_RXDO	UART_0 Receive
2	VSNR	Sensor Supply	28†	UART_TXDO	UART_0 Transmit
3	INT3	GPIO	29	PWO	GPIO/PWM
4	INT2	GPIO	30	PW1	GPIO/PWM
5	INT1	GPIO	31	PW2	GPIO/PWM
6	INT0	GPIO	32	PW3	GPIO/PWM
7††	CC_CCA	Radio Signal	33	PW4	GPIO/PWM
8†	LED3	Green LED	34	PW5	GPIO/PWM
9†	LED2	Yellow LED	35	PW6	GPIO/PWM
10†	LED1	Red LED	36†	ADC7	ADC CH7, JTAG TDI
11	RD	GPIO	37†	ADC6	ADC CH6, JTAG TDO
12	WR	GPIO	38†	ADC5	ADC CH5, JTAG
13	ALE	GPIO	39†	ADC4	ADC CH4, JTAG
14	PW7	GPIO	40	ADC3	GPIO/ADC CH3
15	USART1_CLK	USART1 Clock	41	ADC2	GPIO/ADC CH2
16††	PROG_MOSI	Serial Program MOSI	42	ADC1	GPIO/ADC CH1
17††	PROG_MISO	Serial Program MISO	43	ADC0	GPIO/ADC CH0
18††	SPI_CLK	SPI Serial Clock	44	THERM_PWR	Temp Sensor Enable
19	USART1_RXD	USART1 Receive	45	THRU1	Thru Connect 1
20	USART1_TXD	USART1 Transmit	46	THRU2	Thru Connect 2
21	I2C_CLK	I2C Bus Clock	47	THRU3	Thru Connect 3
22	I2C_DATA	I2C Bus Data	48††	RSTN	Reset (Neg.)
23	PWM0	GPIO/PWM0	49	PWM1B	GPIO/PWM1B
24	PWMIA	GPIO/PWM1A	50	VCC	Digital Supply
25	AC+	GPIO/AC+	51	GND	Ground
26	AC-	GPIO/AC-			

†Shared use ††DO NOT use → For in-system programming ("ISP")

The Table 3-3 shows the 51-pin expansion connector for the MICA2 and the pins that are available for user application:

Table 3-3. MICA2 51-pin Connector Interface

Pin	Name	Description	Pin	Name	Description
1	GND	Ground	27†	UART_RXDO	UART Receive
2	VSNR	Voltage (battery	28†	UART_TXDO	UART Transmit
3	INT3	GPIO	29	PWO	GPIO/PWM
4	INT2	GPIO	30	PW1	GPIO/PWM
5	INT1	GPIO	31	PW2	GPIO/PWM
6	INT0	GPIO	32	PW3	GPIO/PWM
7†	BAT_MON	Battery Voltage Monitor	33	PW4	GPIO/PWM
8†	LED3	Green LED	34	PW5	GPIO/PWM
9†	LED2	Yellow LED	35	PW6	GPIO/PWM
10†	LED1	Red LED	36†	ADC7	GPIO/ADC CH7, JTAG
11	RD	GPIO	37†	ADC6	GPIO/ADC CH6, JTAG
12	WR	GPIO	38†	ADC5	GPIO/ACD CH5, JTAG
13	ALE	GPIO	39†	ADC4	GPIO/ADC CH4, JTAG
14	PW7	GPIO	40	ADC3	GPIO/ADC CH3
15	USART_CLK	USART Clock	41	ADC2	GPIO/ADC CH2
16††	PROG_MOSI	Programmer Pin	42	ADC1	GPIO/ADC CH1
17††	PROG_MISO	Programmer Pin	43	ADC0	GPIO/ADC CH0
18††	SPI_CLK	Radio Clock	44	THERM_PWR	GPIO
19	USART1_RXD	USART1 Receive	45	THRU1	Thru User Connect
20	USART1_TXD	USART1 Transmit	46	THRU2	Thru User Connect
21	I2C_CLK	I2C Bus Clock	47	THRU3	Thru User Connect
22	I2C_DATA	I2C Bus Data	48††	RSTN	Micro Processor Reset
23	PWMIO	GPIO	49	PWM1B	GPIO
24	PWMIA	GPIO	50	VCC	Voltage (battery)
25	AC+	GPIO	51	GND	Ground
26	AC-	GPIO			

†Shared use

††DO NOT use

For in-system programming ("ISP")

3.2 ATmega128 Resources

The ATmega128L and ATmega1281 microprocessors run both the user's application and the *XMesh* protocol stack. The table below summarizes the internal and external resources of the ATmega128 family of microprocessors:

Table 3-4. Resources of the ATmega128 family Microprocessors

Resource	ATmega128L	ATmega1281	Information
Program Memory (Flash Memory)	128K Bytes	128K Bytes	This memory stores the application code. It is programmed through an MIB base station or using OTAP. When reprogrammed, the entire memory is erased except for the bootloader section.
SRAM	4K Bytes	8K Bytes	This memory section is used to store user application parameters, XMesh variables and TinyOS variables. It also contains the stack.
EEPROM	4K Bytes	4K Bytes	This memory is used to store persistent values such as mote_id, group_id, radio channel etc.
Timers	4 Timers, two 8 bit, two 16 bit	4 Timers, two 8 bit, two 16 bit	**TIMER0**: In ATmega128L (8 bit) is used by TinyOS and is available to the user via the standard TinyOS clock services. In ATmega1281 (8 bit) is not available to the user on the IRIS, it is used by the TinyOS radio stack and cannot be used otherwise **TIMER1**: (16 bit) is available to the user **TIMER2**: In ATmega128L (8 bit) is only available to the user on the MICA2. For MICAz it is used by the TinyOS radio stack and cannot by used otherwise. In ATmega1281 (8 bit) is used by TinyOS and is available to the user via the standard TinyOS clock services.. **TIMER3**: (16bit) is available to the user.
SPI Bus	n/a	n/a	The SPI bus is reserved exclusively for the radio interface and is not available for user applications. The SPI bus is also used during reprogramming by the MIB units.
I2C Bus	n/a	n/a	This is a standard serial interface to many sensors
UART	2	2	The processor has two UARTs that can be run in either an asynchronous or synchronous mode. UART0 is used for base station communication. UART1 is available to users. The control pins for this uart are shared with the serial flash.
ADC	8 channels	8 channels	There is a 10 bit ADC available for users. On MICA2 one channel is allocated for the radio's RSSI. The ADC inputs are also used for JTAG so users should try to use other ADC inputs if possible if they wish to use the JTAG capability.
GPIO			There are many general purpose I/O lines available. Some of these support additional functionality (see ATmega128L or ATmega1281 manual as appropriate)
External Clock (High Speed)	7.3728 MHz	7.3728 MHz	This crystal speed is chosen to generate correct UART baud rates (57.6K baud). It is only needed for base station Motes that communicate over the UART or other user applications that communicate to external serial devices. Normally a non-base station mote is fuse programmed to use an internal 8 MHz clock as this clock has a faster start-up time and reduces the overall power consumption for a low-power mesh. The high speed clock is off when the MICA is sleeping.

External Clock (Low Speed)	32 kHz	32 kHz	In ATmega128L, this clock is used for TinyOS timing (TIMER0 in ATmega128L and TIMER2 in ATmega1281). It is always running even when the mote is sleeping as it's used to wake-up the mote after the required sleep interval.

3.3 Using ATmega Resources

3.3.1 General Port Input/Output (GPIO) Pins

GPIO enables direct control of individual CPU pins:

Table 3-5. ATmega128L GPIO Pin Modes

Mode	Action
Output Mode	Set a pin high
	Clear a pin to low
Input Mode	Read a pin's state (high or low)

The ATmega has ports named A-G, each with pins named 0-7.

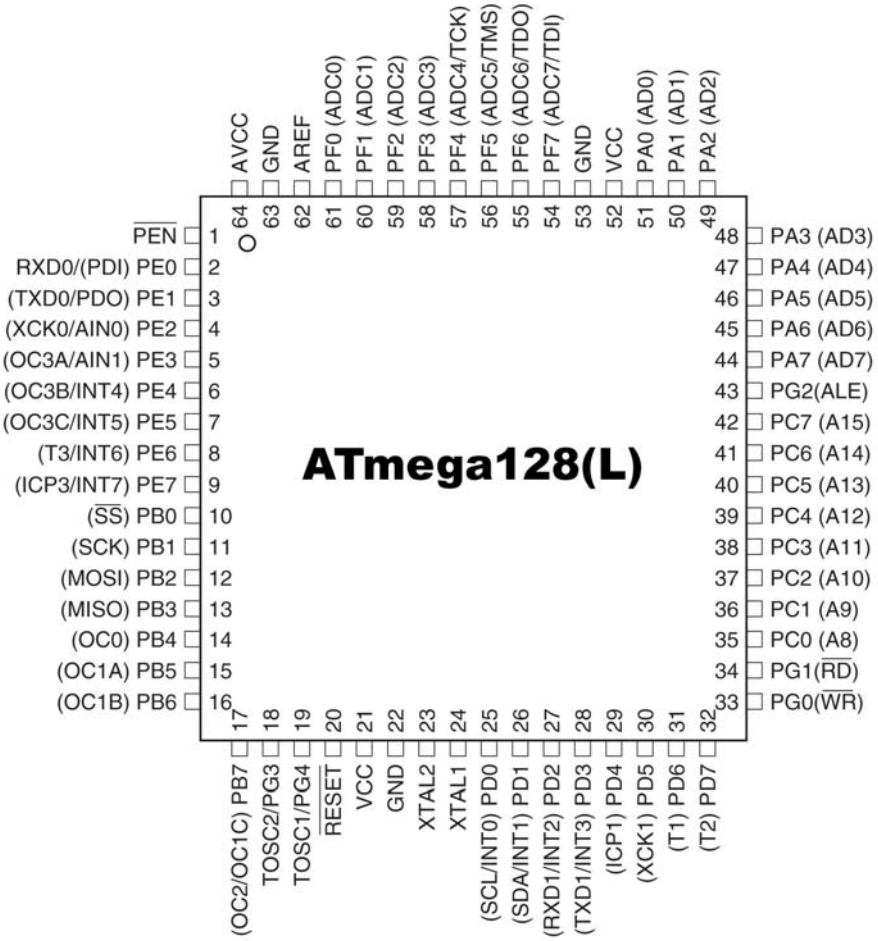


Figure 3-2. ATmega128L Microprocessor Pinout

The ATmega128L can operate up to 6 volts maximum power input and down to 2.4V. Typical operation is from 3.6V to 2.4V. The ATmega1281V can operate up to 6 volts maximum voltage input and down to 1.8V. The output voltage of the GPIO and other pins on the processor will track the operating voltage (i.e. when turned on they will be at the operating voltage).

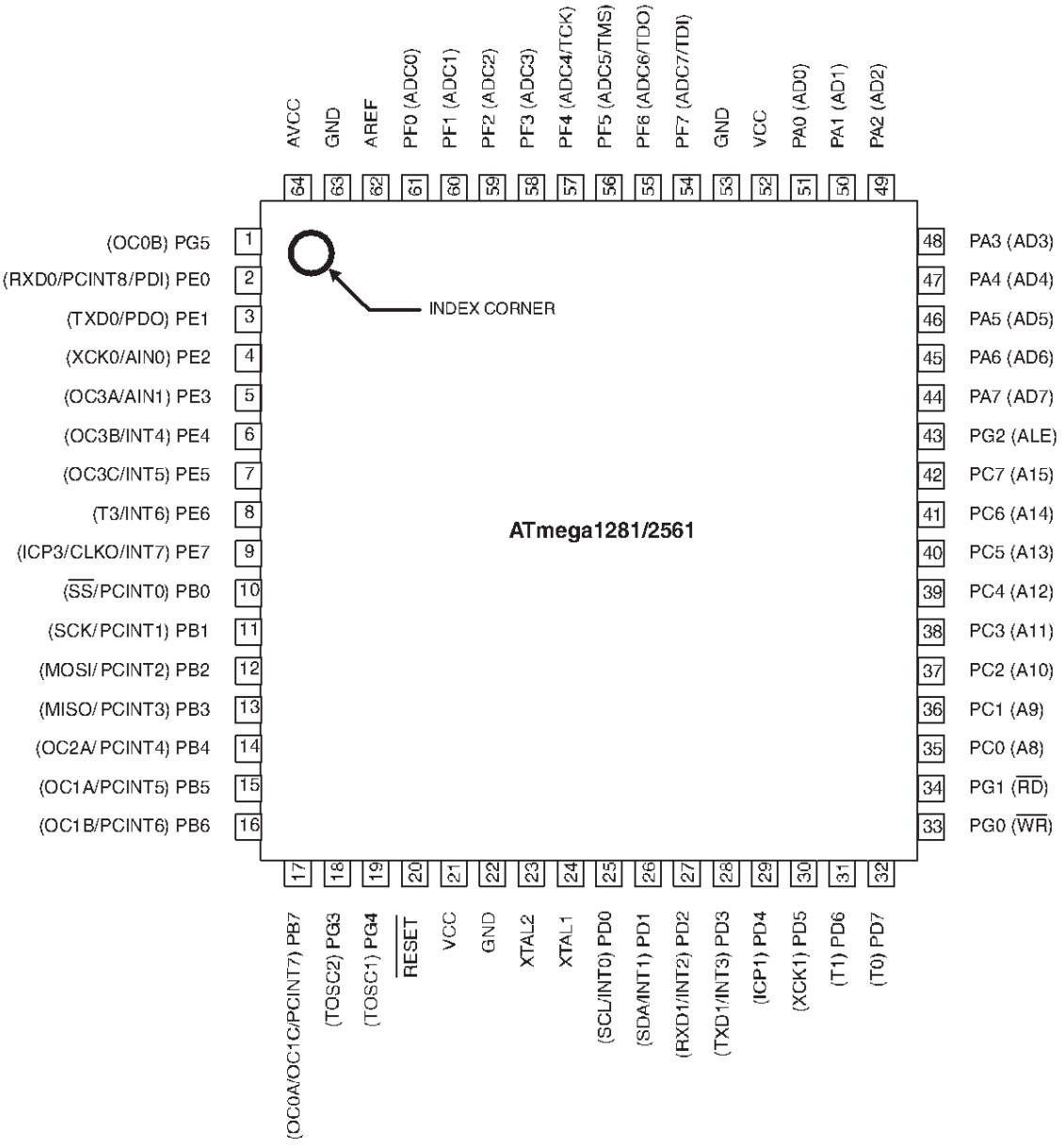


Figure 3-3. ATmega1281 Microprocessor Pinout

⚠ **WARNING:** The MICA2 and MPR600 radio is rated to 5V. The MICAz, IRIS and M2110 radio is rated only to 3.6V.

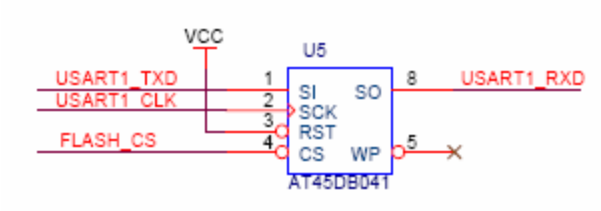
The maximum output current per I/O pin is 40 mA and the maximum current for the processor is 200 mA.

3.3.2 UARTs

The ATmega128 has two UART ports, UART0 and UART1. They can operate in both an asynchronous and synchronous (using a clock) mode. The external clock for the MICA2 and MICAz use a 7.3228 MHz oscillator which generates precise timing for these UARTs to support high baud rates.

⚠ WARNING: The internal RC oscillator does not support high baud rates. Check the ATmega128 manual.

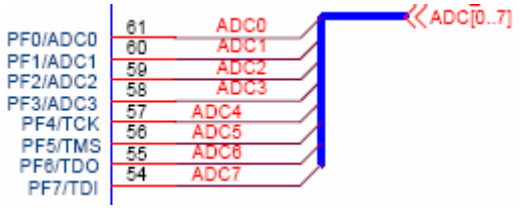
UART0 is used by the base station mote for communication to a client device and configured as the default I/O serial communication port by TinyOS (see XMeshBase chapter). UART1 is available to users. The UART transmit and receive pins are shared with the serial flash which is also used by OTAP (see XMesh Services). If the mote is communicating with another serial device through UART1 users must design the interface so that the external device's transmit pin (which would be connected to UART1's receive pin) defaults to a high impedance state on reset. Otherwise OTAP will not be able to access the serial flash.



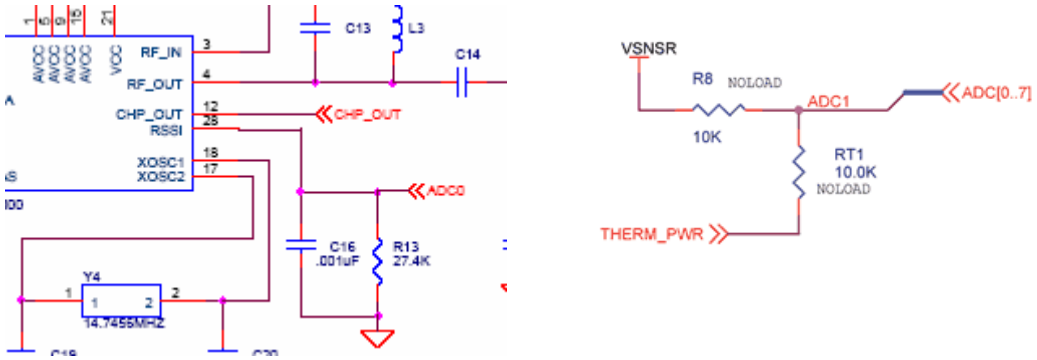
⚠ WARNING: UART1's transmit and receive pins are shared with the external serial flash chip which is used for OTAP.

3.3.3 ADC

The ATmega128 has an internal 10 bit ADC which gives a resolution of 1 part in 1024 (0.1%). The diagram below shows the connection to the ATmega128 pins. ADC channels 4-7 share the JTAG TCK, TMS, TDO and TDI pins. If users want to interface analog sensors to these channels and use JTAG, use a 1K-10K resistor between the output of the sensor and input to the ADC channel so that the sensor output will not interfere with JTAG. When JTAG is operational these channels cannot measure sensor signals.



Some of the ADC channels are dedicated to on board peripherals for the MICA2. ADC0 is used to measure the RSSI (RF signal strength) from the Chipcon1000 radio and is not available. Also, ADC1 is wired to a thermistor for temperature measurements but this channel can be shared with another analog input.



The ADC uses the battery voltage as a full scale reference. This means the full scale of the ADC (10 bit or 1023) is proportional to the battery voltage. For example, when the battery voltage is at 3.2V an ADC value of 1023 will be measure for a full scale voltage input voltage of 3.2V. But when the battery voltage changes to 2.7 volts the full scale will now correspond to this battery voltage.

3.3.4 SPI Bus

The SPI ports are master/slave synchronous serial ports. The SPI bus on both the MICA2 and MICAz are dedicated to the radio interfaces. They are also used during programming to load code.

3.3.5 I2C

This port is a low speed serial interface that supported by many sensor and devices. It is available to users and supported by several Crossbow sensor boards.

3.3.6 The hardware.h File

In the ***/MoteWorks/tos/platform*** directory there are other directories for each hardware platform (such as MICAz, MICA2) supported by *MoteWorks*. This file mainly maps the processors I/O pins to signal names used by the application and TinyOS code. For example:

```
TOSH_ASSIGN_PIN (RED_LED, A, 2);
```

assigns the red led control pin of the ATmega128 (Port A, Pin2) to the name RED_LED. This allows the red led to called by avr functions (see below) directly within the user's code.

Processor pins can also be remapped using an alias statement:

```
TOSH_ALIAS_PIN (name, other_name)
```

TinyOS provides several macros to set these pins as described in Table 3-6.

Table 3-6. TinyOS Macro for I/O Pins

MACRO	Action
TOSH_SET_##name##_PIN()	Set the named output pin to high
TOSH_CLR_##name##_PIN()	Set the named output pin to low
TOSH_READ_##name##_PIN()	Read the named input pin

MACRO	Action
TOSH_MAKE_##name##_OUTPUT()	Define the pin as an output
TOSH_MAKE_##name##_INPUT()	Define the pin as an input

☑ EXAMPLE

An example of using these macros is:

```
TOSH_ASSIGN_PIN(RED_LED, A, 2);
TOSH_MAKE_RED_LED_OUTPUT();
TOSH_SET_RED_LED_PIN();
```

⚠ **WARNING:** The _SET_ command sets the ATmega128 pin high. This turns off the LED. The _CLR_ macro turns on the LED. Consult the schematics that explain how to turn on/off the peripherals.

3.3.7 Interrupts

In the AVR-LIBC environment, convenient macros are predefined to point to interrupt routines with predetermined names. By using the appropriate name, routines will be called when the corresponding interrupt occurs. The ATmega128 library provides a set of default interrupt routines as shown in Table 3-7 and Table 3-8 for ATmega128L and ATmega1281 respectively.

Table 3-7. ATmega128L Interrupt Routines

Interrupt Name	Description	Notes
SIG_INTERRUPT0	External Interrupt0	
SIG_INTERRUPT1	External Interrupt1	
SIG_INTERRUPT2	External Interrupt2	
SIG_INTERRUPT3	External Interrupt3	
SIG_INTERRUPT4	External Interrupt4	Named INT0 on expansion conn.
SIG_INTERRUPT5	External Interrupt5	Named INT1 on expansion conn.
SIG_INTERRUPT6	External Interrupt6	Named INT2 on expansion conn.
SIG_INTERRUPT7	External Interrupt7	Named INT3 on expansion conn.
SIG_OUTPUT_COMPARE2	Output Compare2 Interrupt	
SIG_OVERFLOW2	Overflow2 Interrupt	
SIG_INPUT_CAPTURE1	Input Capture1 Interrupt	
SIG_OUTPUT_COMPARE1A	Output Compare1(A) Interrupt	
SIG_OUTPUT_COMPARE1B	Output Compare1(B) Interrupt	
SIG_OVERFLOW1	Overflow1 Interrupt	
SIG_OUTPUT_COMPARE0	Output Compare0 Interrupt	
SIG_OVERFLOW0	Overflow0 Interrupt	

Interrupt Name	Description	Notes
SIG_SPI	SPI Interrupt	
SIG_UART_RECV UART(0)	Receive Complete Interrupt	
SIG_UART1_RECV UART(1)	Receive Complete Interrupt	
SIG_UART_DATA UART(0)	Data Register Empty Interrupt	
SIG_UART1_DATA UART(1)	Data Register Empty Interrupt	
SIG_UART_TRANS UART(0)	Transmit Complete Interrupt	
SIG_UART1_TRANS UART(1)	Transmit Complete Interrupt	
SIG_ADC ADC	Conversion complete	
SIG_EEPROM	Eeprom ready	
SIG_COMPARATOR	Analog Comparator Interrupt	

Table 3-8. ATmega1281 Interrupt Routines

Interrupt Name	Description	Notes
SIG_INTERRUPT0	External Interrupt0	
SIG_INTERRUPT1	External Interrupt1	
SIG_INTERRUPT2	External Interrupt2	
SIG_INTERRUPT3	External Interrupt3	
SIG_INTERRUPT4	External Interrupt4	Named INT0 on expansion conn.
SIG_INTERRUPT5	External Interrupt5	Named INT1 on expansion conn.
SIG_INTERRUPT6	External Interrupt6	Named INT2 on expansion conn.
SIG_INTERRUPT7	External Interrupt7	Named INT3 on expansion conn.
SIG_PIN_CHANGE0	Pin Change Interrupt Request0	
SIG_PIN_CHANGE1	Pin Change Interrupt Request1	
SIG_PIN_CHANGE2	Pin Change Interrupt Request2	
SIG_WATCHDOG_TIMEOUT	Watchdog Time-out Interrupt	
SIG_OUTPUT_COMPARE2A	Output Compare2(A) Interrupt	
SIG_OUTPUT_COMPARE2B	Output Compare2(B) Interrupt	
SIG_OVERFLOW2	Overflow2 Interrupt	
SIG_INPUT_CAPTURE1	Input Capture1 Interrupt	
SIG_OUTPUT_COMPARE1A	Output Compare1(A) Interrupt	
SIG_OUTPUT_COMPARE1B	Output Compare1(B) Interrupt	
SIG_OUTPUT_COMPARE1C	Output Compare1(C) Interrupt	
SIG_OVERFLOW1	Overflow1 Interrupt	
SIG_OUTPUT_COMPARE0A	Output Compare0(A) Interrupt	

Interrupt Name	Description	Notes
SIG_OUTPUT_COMPARE0B	Output Compare0(B) Interrupt	
SIG_OVERFLOW 0	Overflow0 Interrupt	
SIG_SPI	SPI Interrupt	
SIG_USART0_RECV	UART(0)Receive Complete Interrupt	
SIG_USART1_RECV	UART(1)Receive Complete Interrupt	
SIG_USART0_DATA	UART(0)Data Register Empty Interrupt	
SIG_USART1_DATA	UART(1)Data Register Empty Interrupt	
SIG_USART0_TRANS	UART(0)Transmit Complete Interrupt	
SIG_USART1_TRANS	UART(1)Transmit Complete Interrupt	
SIG_ADC	ADC Conversion complete	
SIG_EEPROM_READY	Eeprom ready	
SIG_COMPARATOR	Analog Comparator Interrupt	

TinyOS supplies two macros to use for interrupt handlers:

- **TOSH_INTERRUPT(signame):** executes with interrupts enabled. (i.e. another interrupt can be serviced while this routine is executing).
- **TOSH_SIGNAL(signame):** executes with interrupts disabled. (i.e. another interrupt will not be serviced while this routine is executing).

☑ EXAMPLE

An example of these handlers are

```
TOSH_SIGNAL(SIG_UART0_RECV) {
    if (inp(UCSR0A) & (1 << RXC))
      signal UART.get(inp(UDR0));
  }
TOSH_INTERRUPT(SIG_OUTPUT_COMPARE1A) {
       signal Timer1.fire();
 }
```

3.4 Low Power Operation

Achieving low power operation requires attention to both the electrical interface and software sensor code. The ATmega128 processor is very good at low power operation but if the I/O pins are not programmed correctly, the supply current can increase by hundreds of µAs.

3.4.1 HPLPowerManagement

TinyOS supplies a power management component, `HPLPowerManagementM`, which will monitor the interrupt state of the processors peripherals. The `HPLPowerManagement.adjustPower` routine checks several registers to see if peripherals are active. Based on these registers it will set the (SM2, SM1, and SM0) bits in the MCUCR CPU register to enable one of the following power down modes:

- **Idle:** This runs at about 50% of the full current or about 4 mA for the ATmega128. In this mode any interrupt will wake-up the processor.
- **Power Save:** This runs at about 15µA. In this mode only Timer0 interrupt wakes the processor (also external interrupts).

`HPLPowerManagement.adjustPower` is only executed if the `HPLPowerManagement.enable()` command has been executed. The following registers are presently checked by `HPLPowerManagement` to determine which sleep modes to enable:

- TIMSK (timer interrupt mask register) - Checks if any timer (except Timer0) is enabled for interrupts)
- UCSR0B and UCSR1B - Checks if UART0 or UART1 is enabled for a receive or a transmit interrupt.
- ADCSR to see if the ADC is enabled.

The power state of the processor is not set by `HPLPowerManagementM`. It only sets the SM2…SM0 bits. The processor will not change power states until the SE (Sleep Enable) bit of the MCUCR register is set to one. This is done by the TinyOS scheduler. When there are no additional tasks on the queue it will enable SE, setting power state (idle, power save) as determined by `HPLPowerManagement`.

Several components, such as the radio stack and `Timer0` automatically enable `HPLPowerManagment`.

3.4.2 Testing for low power operation

1. Run the *TestSleep* application (***/MoteWorks/apps/examples/TestSleep***) on the MICA2 or MICAz without a sensor attached. This application does not use the radio; it only toggles a led every 5 seconds or so while keeping the processor in a sleep state. The battery current will alternate from about 3 mA with the led on to approximately15 µA with the led off.
2. Attach the sensor. Modify *TestSleep* to keep the sensor in an off state. Measure the increased battery current when the led is off. This is the lowest current state the unit can achieve attached to the sensor.
3. Modify *TestSleep* to turn-on the sensor when the led is on. Measure the current. Subtract this from the led current (~3mA). This is the lowest current state the unit can achieve when the sensor is on.

⚠ **WARNING:** The JTAG fuse for the ATmega128 must be disabled to achieve low power operation. If this fuse is on the minimum current is around 3mA. The JTAG fuse is normally programmed to be disabled. Refer to Appendix B.

Do not measure the current with the Mote on the MIB programming board as this will increase the current. Typically the current is measured between the positive battery terminal and the input connector on the Mote.

3.5 Optimizing for Battery Operation

The Table 3-9 shows some standard battery configurations and operational voltages:

Table 3-9. Standard Battery Configurations and Operating voltages

Mote Hardware Platform	Standard Battery (# required)	Typical Battery Capacity (mA-hr)	Practical Operating Voltage Range (V)*
MICAz	AA (2)	2000, Alkaline	3.6 to 2.5
MICA2	AA (2)	2000, Alkaline	3.6 to 2.5

The battery life is dependant on which peripherals are active and their associated duty cycles. The Table 3-10 shows typical operational currents for the MICA peripherals.

Table 3-10. Typical Operational Currents for MICA peripherals

Operation	MICAz (mA)	MICA2 (mA)	IRIS (mA)
Microprocessor, full operation	8	8	6
Microprocessor, sleep	0.020	0.020	0.010
Radio, receive	19.7	7	16
Radio, transmit (@1 mW power)	17	10	17
Radio, sleep	0.001	0.001	0.001
Serial flash memory, write	15		
Serial flash memory, read	4		
Serial flash memory, sleep	0.002		

XMesh-LP in the default configuration achieves approximately 220 µA of average current usage (no sensor board) with the default configuration of:

- One data transmission every 3 minutes
- Radio period length of 128 msec (listening at 8 times/second).

The current consumption can be increased or decreased by changing the default levels. Expected battery life times for this average current level is shown in Table 3-11 below:

Table 3-11. Typical Battery Life for Various Battery Types

Battery Type	Capacity (mA-hr)	Expected Operation (yrs)
AA	2000	1
C	6000	3
D	12000	6

When a sensor board is added the average current consumption will increase. Designing a low power sensor interface and control strategy is a key to maintaining battery life. TinyOS is highly optimized for low power sensor operation but users must be careful both at a hardware and software level to maintain low power operation. Some of the critical components are:

- The state of all Mote's CPU, GPIO and other control lines must be kept in the correct state during sleep. Setting a single GPIO into the wrong state can add an additional 100 µA of current consumption. Refer to the ATmega128 manual for more specific information.
- Many sensors are very low power, and require only a few milliamps of power. Consider powering them directly from a GPIO line of the processor. This allows the processor to easily shut down the power during sleep.
- Be careful of all leakage paths between the battery voltage and ground. A 100K resistor from the battery to ground will introduce 30 µA or so.

3.5.1 Battery Selection

- **Alkaline Batteries:** These are the most common batteries and perhaps the best for sensors that can operate over the Alkaline's voltage range. Two AA alkaline batteries will typically start out at 3.2V but quickly come down to 2.7V. Then the voltage will slowly degrade over time to around 2.3V before the batteries are depleted. MICA2 and MICAz units will operate down to this voltage range.
- **Lithium Batteries:** These batteries will maintain a voltage at 3.2V or greater and are best for sensors that require this minimum level of operating voltage.
- **Lithium Thionyl:** These batteries are good for applications that require wide temperature operations (-40 to +80 ^{0}C) and have large capacities but are expensive.
- **NiCad:** These are rechargeable however have a lower cell voltage (1.2V typically), so stacking 2 batteries is about 2.4V. When stacking 3 cells the initial voltage can be 4.2V which is at the maximum operating voltage of the mote. NiCads also have a fairly large self-discharge rate so are not optimum for infrequent recharge intervals.
- **Temperature range:** All batteries are temperature sensitive. Users need to understand their required operational range and that of the batteries. Alkaline batteries will not work over an industrial temperature range (-40 $^\circ$C to +80 $^\circ$C). Also, at lower temperature ranges they will have several hundred mV of voltage drop.

3.5.2 Battery Output Impedance

Batteries differ from power supplies regarding output impedance (resistance). Power supplies have very low output impedance but many batteries exhibit several ohms of resistance under dynamic conditions. This manifests itself as a voltage drop when the battery current goes from microamps to milliamps. If the voltage drop is greater than 100's mV the radio can be affected. This type of transient behavior is typical of *XMesh-LP* as the mote wakes up many times each second going from ~15 µA of current draw to over 5-30 mA.

The screen shot in Figure 3-4 shows the behavior of a Lithium Thionyl battery with a 1 Ω output impedance (due to a fuse) under these transient conditions for a MICA2 running *XMesh-LP*. The battery voltage (top trace) was AC coupled to the oscilloscope probe so the average signal is centered at zero volts. The bottom trace shows when the sensor is turned on and off. After the sensor turns on the processor sleeps for 300 msec to let the sensor power-on and stabilize. During the first 80 msec there is a 20 mV drop in the battery voltage due to charging the sensor circuit. After the 300 msec delay the processor measures the sensor output (using an external ADC for this unit). Every 125 msec the processor and radio turn on quickly (to measure the RSSI of the radio signal) and the battery voltage drops almost 75 mV. When the radio transmits (150msec pulse) the battery voltage drops by 125 mV. This behavior can sometimes be eliminated by using large capacitors on the battery's output to supply the required current during the transmit cycle.

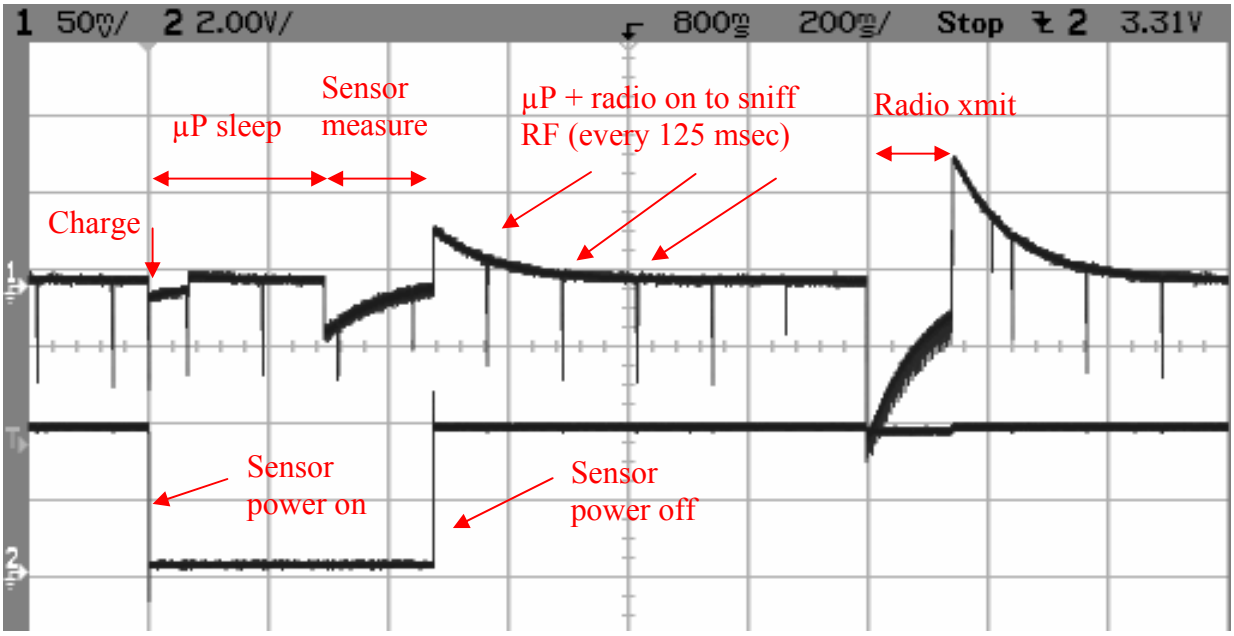

1 50mV/ 2 2.00V/ 800ms 200ms/ Stop 2 3.31V
µP sleep
Sensor measure
µP + radio on to sniff RF (every 125 msec)
Radio xmit
Charge
Sensor power on
Sensor power off

Figure 3-4. Behavior of Lithium Thionyl battery under *XMesh-lp*

3.6 A Low Power Design Example

This section contains an example of an application optimized for low power using *XMesh-ELP*. The sample code is in ***/MoteWorks/apps/examples/TestElp***. The TestElp application is based on the default XMesh-ELP application ***/MoteWorks/apps/examples/TestElp2*** (refer Section 8.5). The application requires following:

1. *XMesh-ELP* (refer to Chapter 8) on a MICAz. The device will act as a 'leaf node'; i.e. it will communicate directly with a powered back bone mesh running *XMesh-HP*.
2. Sample every second, storing the data in SRAM.
3. After twenty samples, transmit the last 20 samples.

Normally *XMesh-ELP* is used for devices that send data at very low data rates. Periodically, between data packet transmits, *XMesh-ELP* would send a health packet and wait for an acknowledgement. If the acknowledge is not received it will stay awake trying to make contact with the base station. Transmitting the health packet and waiting for the acknowledgement consumes more battery current because of the latency time up and down the mesh. If no acknowledge is received after the time-out it will try again. Health packets typically would be sent only every several minutes. For this type of application sending a health packet for every data packet consumes too much energy and does not improve the connectivity to the mesh.

XMesh-ELP allows users to decide when to send data packets and health packets. With this flexibility a power efficient application can be designed by allowing the application to control transmission of either packet type. Different Timers used in the application are outlined in Table 3-12.

Table 3-12. Different Timers used in the Application

Timer	Period (sec)	Type	Description
`UpdateTimer`	1	Repeat	Sets sampling interval, fires WaitTimer
`WaitTimer`	.050	One-shot	Sensor power is turned on and a measurement made
`HealthTimer`	180	Repeat	Fires to signal that a health packet should be transmitted.

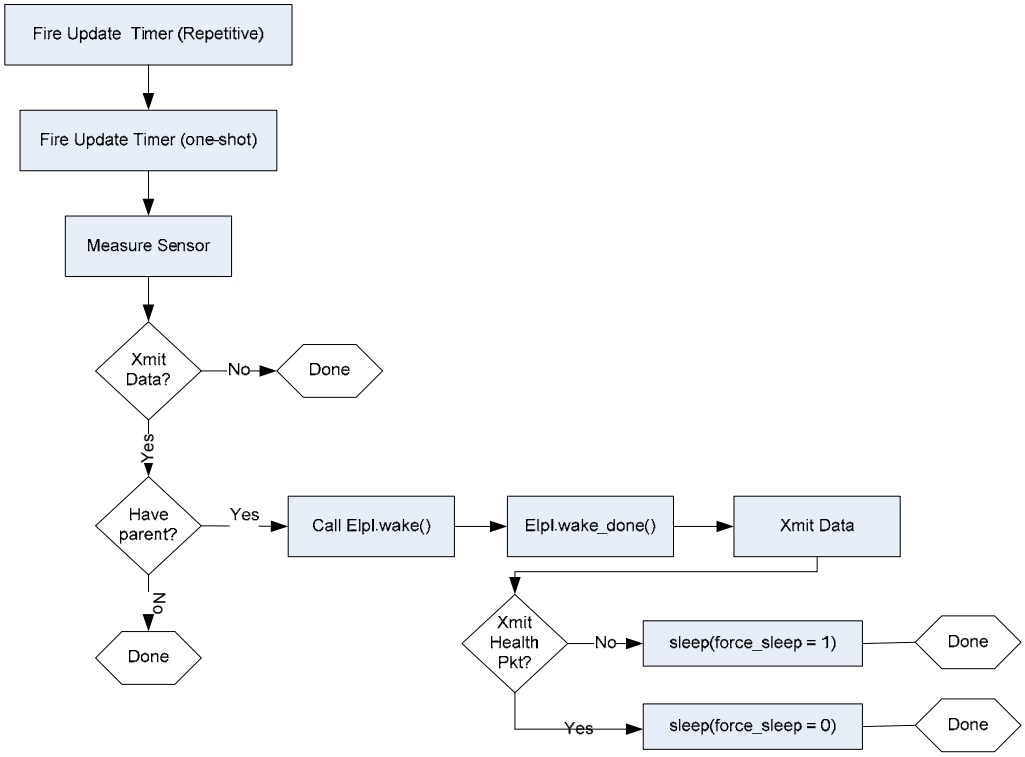
When the mote is powered on, it must join the mesh. It does this by calling `ElpI.route_discover()`:

```
command result_t StdControl.start() {
    call UpdateTimer.start(TIMER_REPEAT, gSampleInterval);
    call HealthTimer.start(TIMER_REPEAT, ELP_SLEEP_MS);
    call XMeshControl.start();
    call ElpControlI.enable();
    call ElpI.route_discover(NUM_ROUTE_DISCOVER_INTS);
    pressureDataPtr = (pressureMsg * ) call COMM.getBuffer(dataMsgPtr, &Len);
    return SUCCESS;
  }
```

During this time the mote will be on all the time (users could modify this to put the mote to sleep for a period of time, then try again if the `ElpI.route_discover_done` returns with a fail). Any data message transmitted during this time will default to the broadcast address (0xffff) and not be forwarded to the base.

⚠ **WARNING:** When joining the mesh the ELP Mote needs to stay awake for several route updates (`ROUTE_UPDATE_INTERVAL`) to join the mesh.

Once the Mote has joined the mesh the normal data transmissions can start. Before each data transmission the radio is forced out of the sleep mode. Once *XMesh* signals that the radio is on data can be transmitted. After the message is transmitted the code detects if it's time to send a health packet. If so the sleep command is restarted with health packets enabled. If not, sleep is called without issuing health packets. In a typical ELP mode operation, for example the XMesh-ELP application ***TestElp2,*** the health packets are generated automatically even when the ELP mote is asleep by ensuring that the health_interval is smaller than the sleep interval. In the default ELP mode the maximum health packet interval is thus constrained by the sleep interval. The user may control the health packet transmission by disabling the automatic generation of health packets while the node is asleep. This can be achieved by setting the health interval to be greater than the sleep interval (refer PressureSensor.h in ***TestElp*** application). The users would now have to create their own health timer to periodically transmit health packets at intervals greater than the sleep interval. Therefore in the ***TestElp*** application, we use a separate health_timer to initiate periodic health packet transmission.



3.7 Estimating the Average Current

The average current can be estimated if the following is known:

- Current of each operational state
- Duty cycle of each operational state

For this application, the operational states are:

1. **Sleep:** The system is in this state approximately 95% of the time.
2. **Timer0:** This timer service is always running as it supplies timer services for all the TinyOS components. For the MICAz this timer wakes every 230 msec for 400 µsec, increments a counter, and goes back to sleep. During this time the processor is using 8 mA of current.
3. **Measure Sensor:** For this application the sensor is on for 50 msec. The ATmega128 is used to measure the sensor output (timer counter) so the lowest power state for the processor is the idle state (4 mA). Also, the sensor itself consumes 400 µA. The measurements are done every second so the duty cycle is 50 msec/1000 msec.
4. **Transmit Data:** This occurs every twenty seconds for the application. The data packet is transmitted in about 4 msec but the MAC layer adds a random back-off of about 4 msec. Also the link level acknowledgement adds about 2 msec for a total of about 10 msec that both the radio and processor are awake.
5. **Health Data:** Health packets are sent only every several minutes. Sending a health packet is similar to the data packet except that it uses end-to-end acknowledgement. The time to receive the acknowledgement depends on the message latency up and down the mesh. Typically for several hops this can be 100 msec to 200 msec. During this time the processor and radio will be on. If a health packet is sent every 3 minutes and the mote is on for 300 msec the duty cycle is 0.017%.

Table 3-13. Calculation of Average Current

Operational State	Current (mA)	Duty Cycle (%)	Avg Current (µA)
Sleep	0.015	95	14
Timer0	8	0.17	13
Measure Sensor	4.4	5	220
Transmit Data	30	0.05	15
Transmit Health	30	0.17	50
Total Average Current			**312**

The screenshot in Figure 3-5 shows the current consumption (vertical axis) of the Mote as a function of time (horizontal axis). Periodically (every ~230 msec) Timer0 fires to service all timers. Once every second the mote wakes up and takes sensor data. Once every 20 seconds the mote also transmits a data packet after taking sensor data.

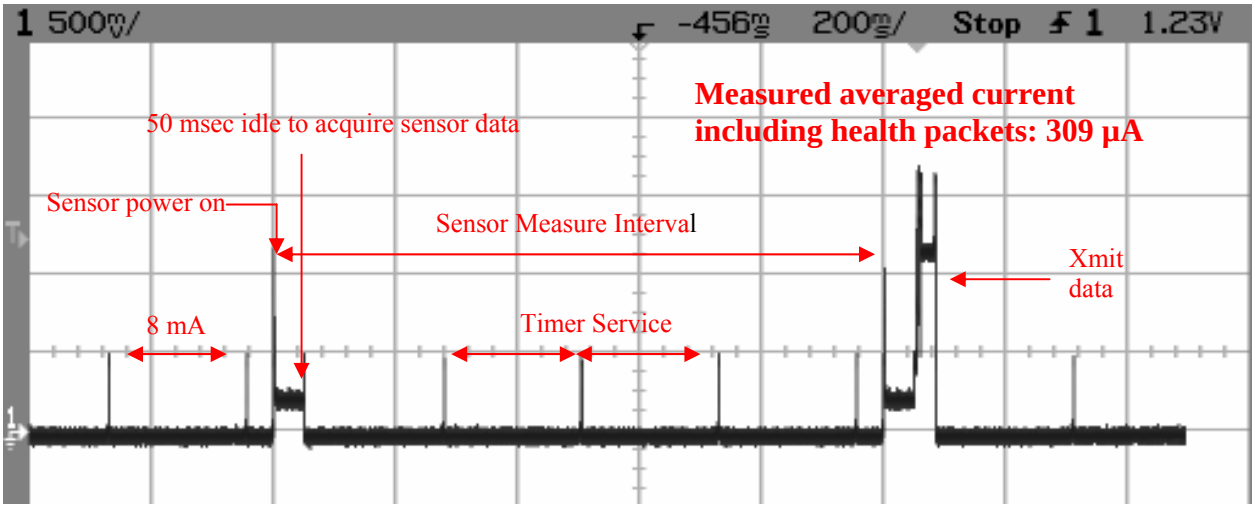


Figure 3-5. Current Consumption of a Mote

3.8 Hardware Debugging Techniques

3.8.1 LEDS

The MICA platforms (MICA2/MICAz) have three LEDs (red, yellow and green) that can be easily used to debug code. TinyOS supplies a component (`LedsC`) which enables turning any led off or on; also toggling the led. Inserting calls to the LEDs in the code supplies a visual indicator. TinyOS also supplies a component, `NoLeds`, which, if wired to, disables the LEDs (refer to Appendix D).

3.8.2 JTAG

The ATmega128 processor offers in-circuit debugging through its JTAG interface. This tool allows users to

- Perform real time in-circuit debug
- Trace program execution directly
- Access CPU registers, RAM, ATmega128 peripherals.
- Set breakpoints.
- Change variables and jump over code

In order to use JTAG the following are required:

- A JTAG pod such as the ones available from Olimex. This device is available with both a serial port or USB connection:

  http://www.olimex.com/dev/avr-jtag.html

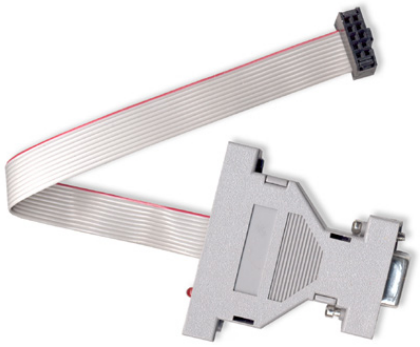


Figure 3-6. Olimex JTAG pod

- A MIB510 or MIB520 programming board. These units contain a JTAG connector which connects to the JTAG pod. The JTAG connector is labeled as J3 (MOTE JTAG) on the MIB510/MIB520.

To setup the JTAG environment:

1. Connect the JTAG pod to a PC serial port or USB port.
2. Connect the JTAG pod's 10 pin header to the MIB510/MIB520. Be careful of the orientation. There is a silkscreen designator "o" by pin 1 of the MIB510 connector. Also, there is a square pad (versus the other 9 round pads) on the bottom side of the MIB510/MIB520 for pin 1. Usually the red wire of the flex cable connecting the JTAG header to the JTAG pod is pin 1. Make sure the polarity is correct.

⚠ **WARNING:** On the MIB510, DO NOT connect the JTAG pod to the ISP (J8) connector. This could erase the code in the ISP processor of the MIB510.

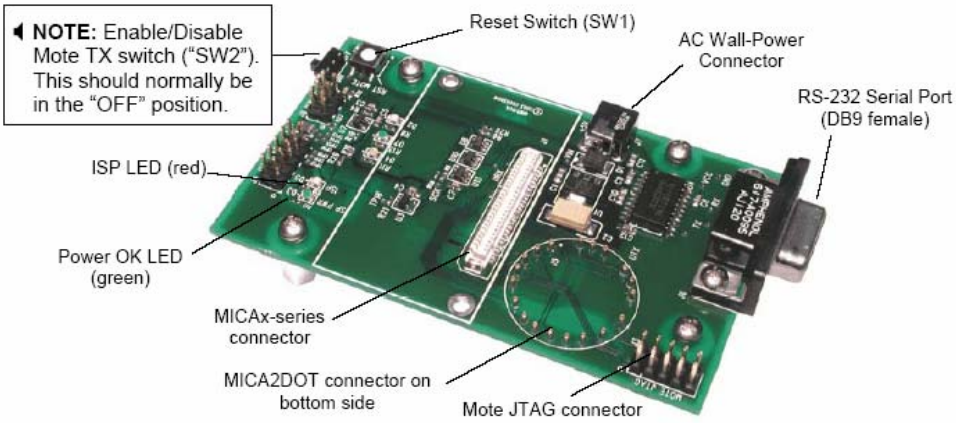

NOTE: Enable/Disable Mote TX switch ("SW2"). This should normally be in the "OFF" position.
Reset Switch (SW1)
AC Wall-Power Connector
RS-232 Serial Port (DB9 female)
ISP LED (red)
Power OK LED (green)
MICAx-series connector
MICA2DOT connector on bottom side
Mote JTAG connector

Figure 3-7. MIB510 Serial Programming Board

3. Mount a MICA2 or MICAz for debugging on the MIB programming board.

Figure 3-8. MIB510 Attached to Atmel JTAG for Debugging

⚠ **WARNING:** Do not attach a sensorboard that uses the analog-to-digital ADC4-ADC7 pins as these pins are used for JTAG.

Normally power is supplied to the JTAG via the MIB board's external power supply. If the pod is configured to supply power to the mote then do not power the MIB board from the external power supply.

4. Setup the environment variables for avarice. This can be done in the PC's environmental variables/system variables:

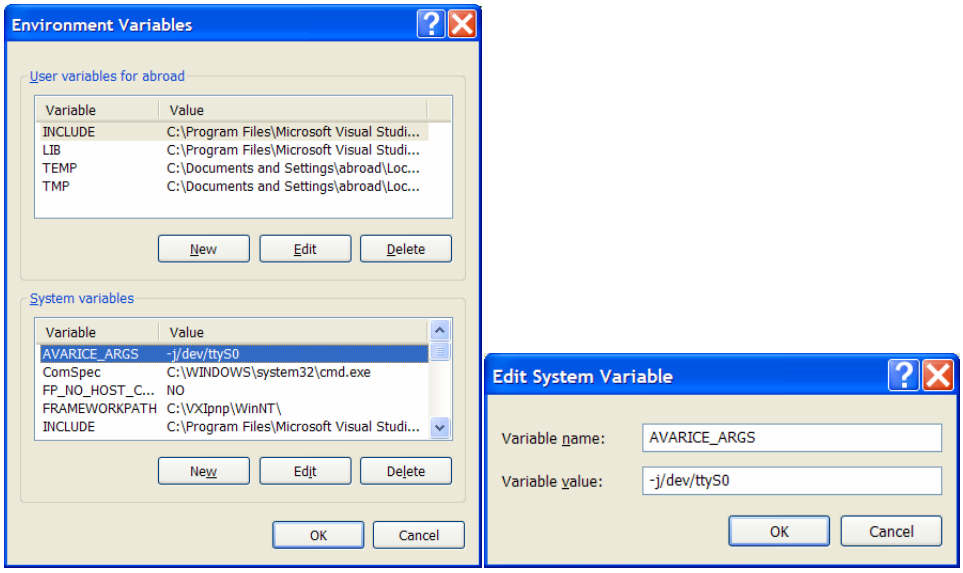


Figure 3-9. Setting Environmental and System Variables of the PC

The example shown above sets the JTAG pod for serial port COM1 (S0).

This also can be done from the Cygwin command line:

```
export AVARICE_ARGS='-j COM1'
```

To build a debug version of an application do:

```
make micaz debug
```
or

```
make mica2 debug
```
or

```
make iris debug
```

⚠ **WARNING:** The `mote_id` address will be 1 and cannot be changed by the normal install process (since this is not used when loading code via JTAG). A different id can be set in the `StdControl.start` routine of the application by coding `TOS_LOCAL_ADDRESS = xx` (where xx is the desired id).

Make sure the JTAG fuse is enabled on the mica platform. This can be done using the fuses script (see Appendix B):

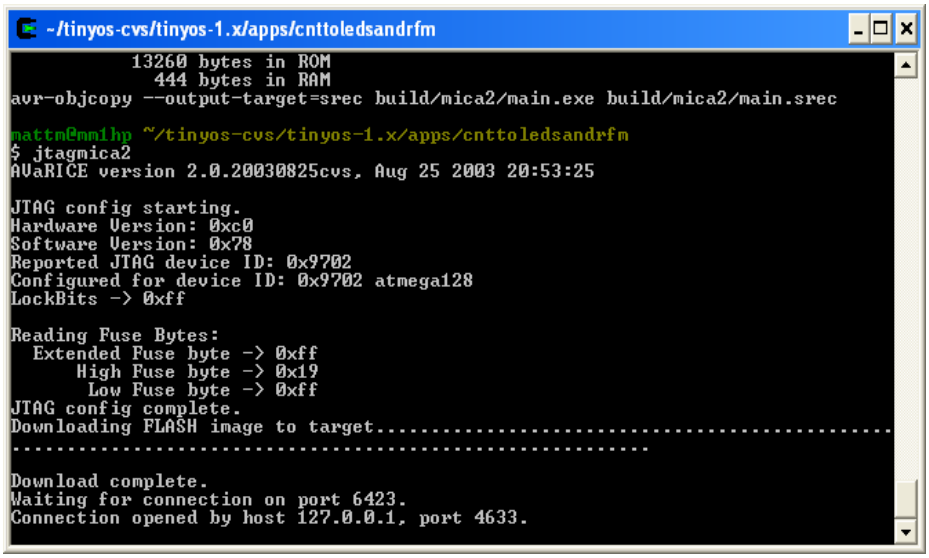
```
fuses jtagen
```

⚠ **WARNING:** The default fuse setting is JTAG disabled. Each time the mote is programmed with make install <platform> the JTAG fuse will be disabled.

Start *avr-ice* by typing:

```
ice-insight ./build/mica2/main.exe
ice-insight ./build/micaz/main.exe
ice-insight ./build/iris/main.exe
```

or ice-gdb (if it doesn't work). This should download the code image into the Mote via JTAG:


~/tinyos-cvs/tinyos-1.x/apps/cnttoledsandrfm
13260 bytes in ROM
444 bytes in RAM
avr-objcopy --output-target=srec build/mica2/main.exe build/mica2/main.srec
mattm@mn1hp ~/tinyos-cvs/tinyos-1.x/apps/cnttoledsandrfm
$ jtagmica2
AVaRICE version 2.0.20030825cvs, Aug 25 2003 20:53:25
JTAG config starting.
Hardware Version: 0xc0
Software Version: 0x78
Reported JTAG device ID: 0x9702
Configured for device ID: 0x9702 atmega128
LockBits -> 0xff
Reading Fuse Bytes:
Extended Fuse byte -> 0xff
High Fuse byte -> 0x19
Low Fuse byte -> 0xff
JTAG config complete.
Downloading FLASH image to target.....
Download complete.
Waiting for connection on port 6423.
Connection opened by host 127.0.0.1, port 4633.

The main screen of the GUI should appear as below. Sometimes this screen is sized incorrectly. This can be overcome by resizing the window.

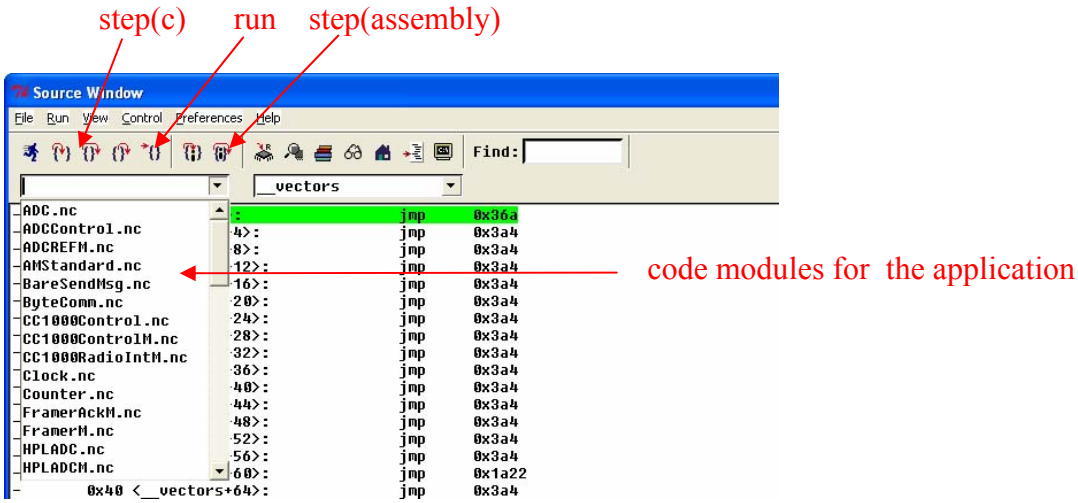


Figure 3-10. The Main Screen of the *ice-insight* GUI

The icons shown will allow:

- View all source code modules linked into the application
- Execute (run) the application or run to a breakpoint
- Step through C code or assembly code.

NOTE: Stepping through the code is difficult as interrupts are usually enabled and the code flow will usually branch to an interrupt handler. Setting breakpoints is more efficient.

3.8.3 Setting Breakpoints

Using breakpoint:

- The " –" at the left side of the screen indicates that a breakpoint should be available. Gcc optimizes the code so not all lines support breakpoint. Even some lines with the "–" mark will not support a breakpoint.
- After running the code, if a breakpoint is encountered, the line will be shown highlighted in green. At this time the code has stopped execution and registers (RAM, etc) can be examined.
- The ATmega128 supports up to 4 hardware breakpoints. These breakpoints are internal to the ATmega128 CPU.

⚠ WARNING: Ice-insight does not give any warnings if the breakpoints have been exceeded. Also, before running ice-insight it's advisable to cycle the power to reset the hardware breakpoints since it does not reset them on power-up.

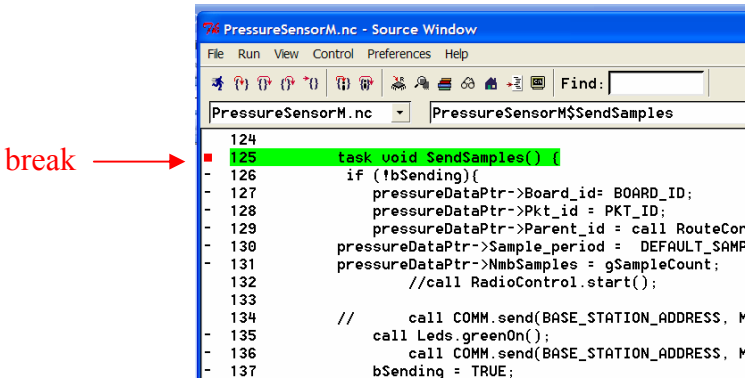


Figure 3-11. Debugging using *ice-insight* GUI

3.8.4 *Examining the CPU registers*

After the CPU is halted (usually through a breakpoint) the CPU registers can be viewed by selecting View>Registers.

Users can

- View all CPU registers including the PC counter (PC), stack pointer (SP) and status register (SREG).
- Change the value in any register by entering a new value and hitting return.
- Restart the program by setting the PC counter to 0x0000, hitting return, and selecting the run icon (see Figure 3-).

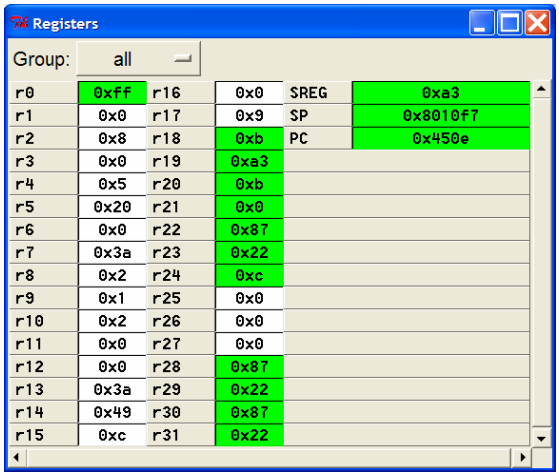
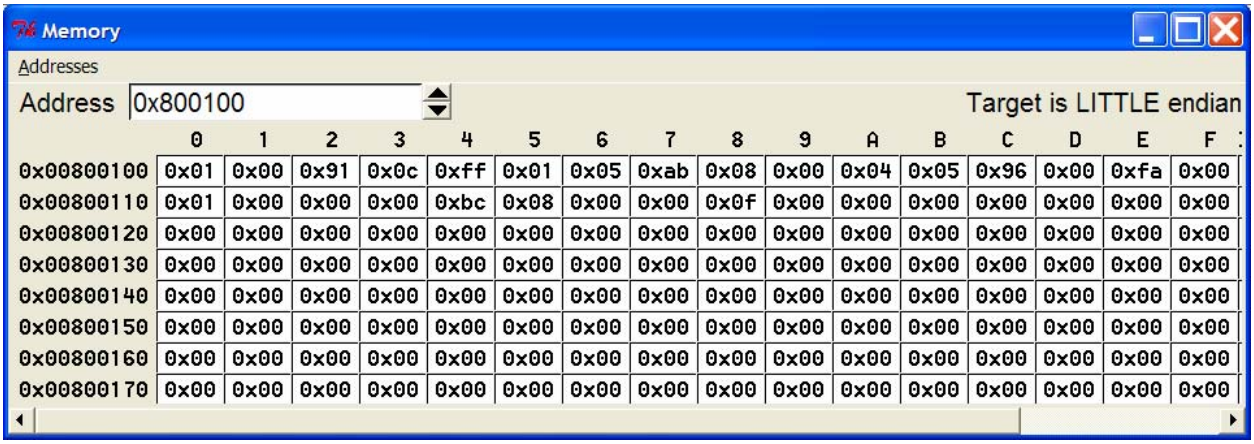


Figure 3-12. Viewing the CPU Registers

3.8.5 *Viewing SRAM*

SRAM can be viewed by selecting View>Memory. Users can:

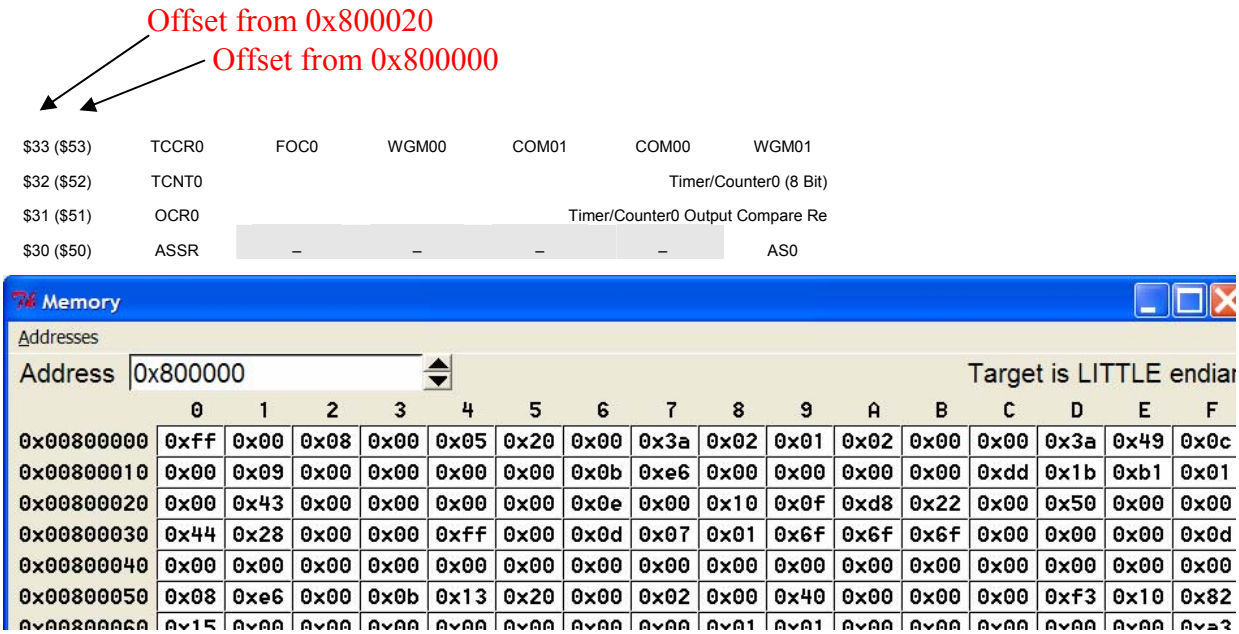
- View and change any section of SRAM
- View and change any of the CPU I/O registers (see Figure 3-12).



	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0x00800100	0x01	0x00	0x91	0x0c	0xff	0x01	0x05	0xab	0x08	0x00	0x04	0x05	0x96	0x00	0xfa	0x00
0x00800110	0x01	0x00	0x00	0x00	0xbc	0x08	0x00	0x00	0x0f	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800120	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800130	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800140	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800150	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800160	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800170	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00

Figure 3-13. Viewing CPU's I/O Registers

The ATmega128 I/O registers are mapped into a high portion of memory starting at 0x800020. The Register Summary at the back of the ATmega128 manual shows all registers and their offset from 0x800020 and 0x800000.


Offset from 0x800020
Offset from 0x800000
$33 ($53) TCCR0 FOC0 WGM00 COM01 COM00 WGM01
$32 ($52) TCNT0 Timer/Counter0 (8 Bit)
$31 ($51) OCR0 Timer/Counter0 Output Compare Re
$30 ($50) ASSR – – – – AS0
Memory
Addresses
Address 0x800000
Target is LITTLE endian

	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0x00800000	0xff	0x00	0x08	0x00	0x05	0x20	0x00	0x3a	0x02	0x01	0x02	0x00	0x00	0x3a	0x49	0x0c
0x00800010	0x00	0x09	0x00	0x00	0x00	0x00	0x0b	0xe6	0x00	0x00	0x00	0x00	0xdd	0x1b	0xb1	0x01
0x00800020	0x00	0x43	0x00	0x00	0x00	0x00	0x0e	0x00	0x10	0x0f	0xd8	0x22	0x00	0x50	0x00	0x00
0x00800030	0x44	0x28	0x00	0x00	0xff	0x00	0x0d	0x07	0x01	0x6f	0x6f	0x6f	0x00	0x00	0x00	0x0d
0x00800040	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x00
0x00800050	0x08	0xe6	0x00	0x0b	0x13	0x20	0x00	0x02	0x00	0x40	0x00	0x00	0x00	0xf3	0x10	0x82
0x00800060	0x15	0x00	0x00	0x00	0x00	0x00	0x00	0x00	0x01	0x01	0x00	0x00	0x00	0x00	0x00	0xa3

Figure 3-14. Viewing CPU Registers (ASSR is at 0x800050)

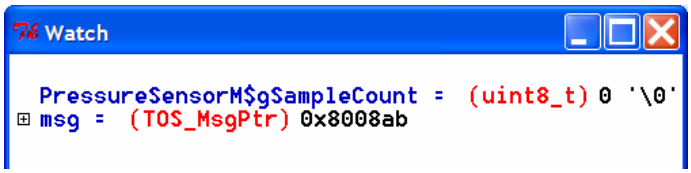
When viewing the assembly code (see Figure 3-15) the instructions show just the offset from 0x800020.

3.8.6 Viewing Variables

Selecting the View>Watch Expressions allows users to enter the names of variables to monitor. There are two types of variables to monitor:

1. **Global parameters:** These are global to the module. To enter these parameters in the watch window requires entering the name of the module + "$" + name of variable. For

example, to watch `gSampleCount` in the `PressureSensorM` module enter `PressureSensorM$gSampleCount` in the watch window and Add entry.



2. **Local parameters:** These are local to the procedure and they are entered directly without the name of the module.

⚠ **WARNING:** Gcc reuses registers. Be careful when viewing local parameters as the values in the register may be reused for other instructions.

3.8.7 *Viewing Assembly Code*

Selecting the SRC+ASM selection on the right side of the screen will display two screens, one with source code and the other with the assembly code. Users can single step through the assembly code by using the assembly step button on the screen toolbar.

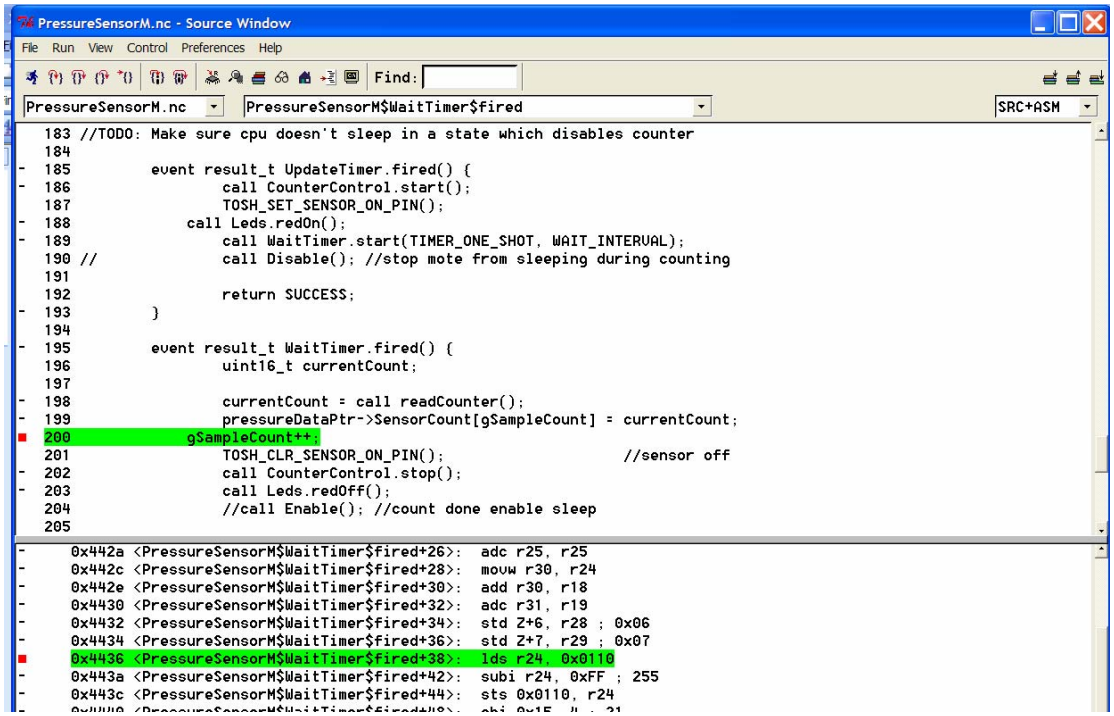


Figure 3-15. Viewing Assembly Code

3.8.8 *SODBUG*

`SODbug` allows users to send `sprintf` type messages directly from the application code to the UART serial port. If the Mote is running on a MIB510/MIB520/MIB600 users can send serial messages directly to any terminal program such as HyperTerminal by configuring 57600 baud, 8 bits, No Parity and 1 Stop Bit.

`SODbug` code is located in the *SODbg.h* file in ***/MoteWorks/tos/interface***.

To use SODbug:

- In the application code insert `sprintf`-type like:

  `SODbg(DBG_PKT, "MYAPP$MsgRcvd:%i\n",data);`

- Include *SODbug.h* and its *#defines* in all code modules that need serial output immediately after the start of the implementation section:

```
implementation {
    #define DBG_PKT  1
    #define SO_DEBUG  1
    #include "SOdebug.h"
```

An example of SODbug is in ***/MoteWorks/apps/examples/SODbug***

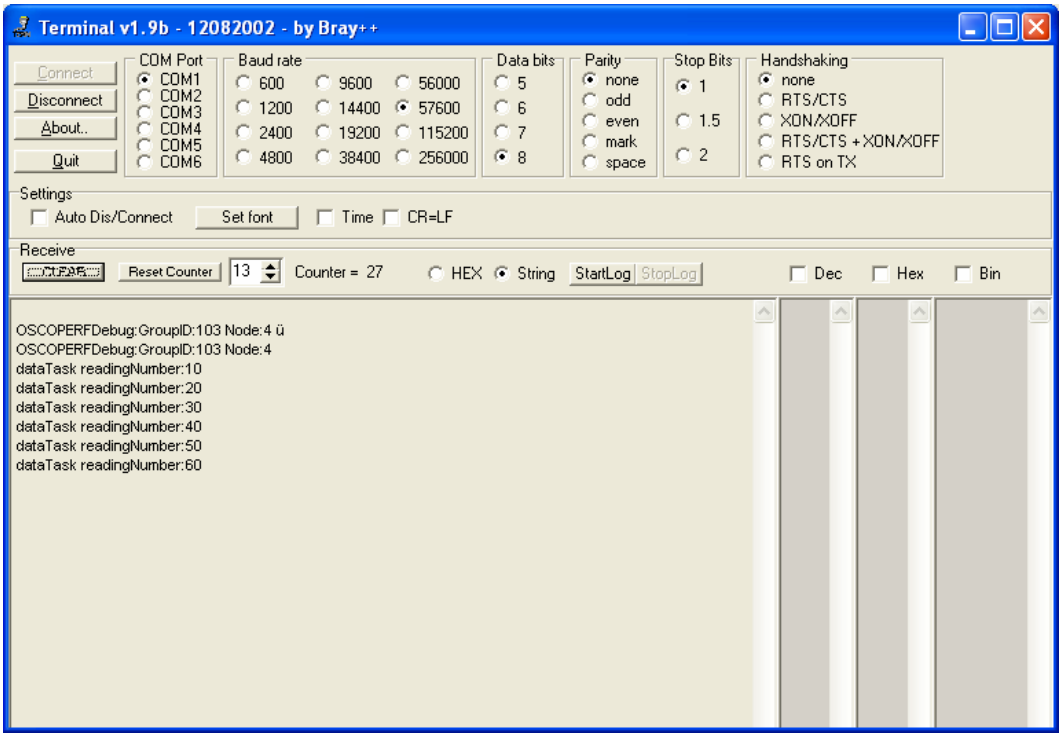


Figure 3-16. Terminal Program showing SODbug

⚠ **WARNING:** SODbug takes over control of UART0. Be careful of conflicts between SODbug and any UART messaging TinyOS may be doing.

4 XMesh Overview

This section gives a general overview of *XMesh* and discusses:

- The different power configurations for *XMesh*
- An overview on how *XMesh* forms an ad-hoc network.

4.1 XMesh Power Configurations

Crossbow sensor networks can run several power strategies. Each strategy is a trade-off between power and data rates. For systems that have continuous power *XMesh-HP* is the best solution. This offers the highest message rate, typically proportional to the baud rate of the radio. For battery operated systems that require multi-month or multi-year life *XMesh-LP* and *XMesh-ELP* are normally used.

4.1.1 XMesh-HP

In this mode the Mote radios and processors are continually powered. This consumes between 15 to 30 mA depending on the type of Mote. Motes can receive messages and transmit at any time. Route Update Messages and Health Messages are sent at a faster rate which decreases the time it takes to form a mesh or for a new mote to join the mesh.

4.1.2 XMesh-LP

The low power mesh can run either time synchronized or asynchronous. The best power efficiency is achieved with time synchronization supported by *XMesh-LP* (see Section 7.1.4). In this mode all motes are time synchronized within ±1 msec. The motes wake-up, typically 8 times/second, time synchronized, for a very short interval to see if the radio is detecting any signal over the noise background. If so, the radio is kept on to receive the signal. This operation typically results in a base level current of 80 µA. The total average current depends on the number of messages received and transmitted. When transmitting data every three minutes the usual power in a 50 node mesh is around 220 µA. The average current to acquire sensor data will increase this. *XMesh-LP* can be configured for even lower power by reducing the wake-up periods and transmitting at lower rates. Also route update intervals are set at a lower rate to conserve power. This also results in a longer mesh formation time.

4.1.3 XMesh-ELP

The ELP mode is only used for leaf nodes that communicate with parent nodes running *XMesh-HP*. A leaf node is defined as a node that does not participate in the mesh, it never routes messages from child motes to parent motes. The ELP version results is very low power because the mote does not need to use the time synchronized wake-up mode to check for radio messages. The mote can sleep for very long times. In this mode the mote maintains its neighborhood list to remember which parents it can select. If it does not get a link level acknowledgement when it transmits to a parent it will find another parent. This can happen very quickly or may take some time if the RF environment or mesh configuration has changed considerably.

The Table 4-1 shows the types of power modes supported by Crossbow Motes.

Table 4-1. XMesh Power Configuration Matrix

Power Mode	MICA2	MICA2DOT	MICAz
XMesh-HP	√	√	√
XMesh-LP (asynchronous and time synchronized)	√	√	Asynchronous only
XMesh-ELP	√	√	√

Table 4-2. XMesh Performance Summary Table

Parameter	XMesh-HP	XMesh-LP	XMesh-ELP
Route Update Interval	36 sec.	360 sec.	36 sec if built using HP 360 sec if built using LP
Data Message Rate	10 sec, typ.	180 sec., typ.	N/A
Mesh formation time	2-3 times Route Update Interval for mesh with average of 2.5 hops		
Average current usage	20-30 mA	<250 µA [1] < 400 µA [2]	50 µA

[1] MICA2-LP using time synchronized mesh.

[2] MICAz-LP using asynchronous mesh

4.2 Forming a Multi-hop Mesh Network

To form and maintain a Mesh network, the following 2 parallel processes are involved:

1. **Link Estimation**

   A node promiscuously listens to radio traffic in its neighborhood and uses that information to populate a neighbor table. It estimates how good it can hear a neighbor by monitoring the sequence numbers in the Multihop header, and runs an EWMA algorithm to smooth out that estimate.

   The neighbor table size is preset by a #define, usually 16 (see Appendix A). If a mote can hear more than 16 neighbors it will evict the lowest quality ones from the table. The base station mote's neighbor table size is set to a larger value of 40 to handle more neighbors. Since the base station does not usually run an application it is not as memory constrained as the children motes.

2. **Parent Selection**

   The node searches its neighbors in the neighbor table and selects the one that will incur the lowest energy cost to be its parent. A neighbor is considered a parent candidate if it:

   - has already joined *XMesh*
   - is not a descendant node for the last 3 RUIs (Route Update Intervals); this is intended to avoid cycles

- is not an ELP node.

An *XMesh* multihop network is formed by having all motes in the network periodically broadcast Route Update Messages, which contains the following information:

1. **Parent ID**: If the node has not yet joined the mesh, this field is 0xFFFF.
2. **Cost:** It tells other motes in the neighborhood how much it will cost to send a message upstream to the base station
3. **Hop count:** The number of hops to send a message to the base station.
4. A list of qualified neighbors and their quality estimate. Due to the TinyOS packet size, each route update message will contain at most 5 neighbors. A neighbor is considered qualified if its receive estimate (defined below) is greater than a threshold (100 for high power, 10 for low power). By default, the size of neighbor table is 16 for the remote mote, 40 for the base station, if there are more than 5 qualified neighbors, the node will sequence through the neighbor list and handle that in multiple, sequential, route update messages.

The Route Update Message will be broadcasted every RUI (Route Update Interval, defined in *Multihop.h*. By default it is set to 36 seconds for high power, and 360 seconds for low power. The actual number is randomized by multiplying a random number, between 0.9 and 1.1, to the defined value).

To better understand the processes, we will first define some related metrics:

RE: Receive Estimate, the radio receive quality of the link from a specific neighbor, computed by applying the EWMA (Exponentially Weighted Moving Average) algorithm to the percentage of the received packet:

New_Estimate = 255*received / (received + missed)

RE = (1-alpha) * RE + alpha * New_Estimate

Where alpha is the EWMA factor, it is a value between 0 and 1 that defines weight of the new estimated value.

SE: Send Estimate**,** the radio transmit quality of the link to a specific neighbor, it is obtained from the route update messages of the neighbor. When a node broadcasts a route update message, it also puts its neighbors' RE in the packet, so neighbors know what the SE is to this node.

NOTE: **SE** and **RE** are normalized to be a value in [0, 255], with 255 being the perfect quality.

LC: Link Cost to a specific neighbor. Once SE and RE to a specific node are known, the LC is computed as:

LC = (1<<18) / (SE * RE)

NOTE: If the link quality is perfect, which means SE and RE are all 255, the LC is then 4. This translates to a cost of 4 per hop, provided that the link quality is perfect.

NC: Neighbor's cost, a value that is obtained from the Route Update Message from a specified neighbor.

OC: The Cost value of sending message to the base. It is calculated as:

$$OC = LC + NC$$

The mote will pick the neighbor with the lowest OC as its parent.

NOTE: The higher the cost value, the more energy is required to make a transmission to the base. *XMesh* then uses the **Minimum Transmission** (MT) cost metric. The purpose of the cost metric is to minimize the total cost it takes to transmit to the base station Mote. Each node in the mesh network will broadcast its cost value. The base station Mote broadcasts a 'zero' cost in its route update messages.

XMesh executes a parent selection task every 8 RUI**s,** it is assumed that a node needs this duration to be long enough to gather information about its neighbor and make good decisions based on the information. *XMesh* speeds up the Mesh formation time by introducing a fast formation mode. Once a node enters this mode (for example, the node just boots up, or loses its old parent etc), it executes the fast formation algorithm and picks a suboptimal parent in order to join the mesh quickly; it will switch to the best parent later. Since a potential parent has to be part of the Mesh to be considered as a parent candidate, the time for a node to join the Mesh is a function of RUI and hop count. As a rule of thumb, the nodes one hop away from the base station will join the Mesh in 1 RUI, nodes two hops away will join the Mesh in 2 RUI2, so on and so forth, and it will take 8 RUIs for the Mesh to get stable.

5 Sending and Receiving XMesh Messages

This section discusses how to send and receive messages from an application via the *XMesh* network. It includes:

- Description of XMesh multihop messages
- *XMesh* Messaging API
- Using the *XMesh* API

5.1 TinyOS Multihop Messages

XMesh messages are TinyOS messages with additional information about the message routing.

Table 5-1. XMesh Message Structure

Component	Description
Header	Composed of standard TOS header and XMesh multihop header
Payload	User data
CRC	CRC check (Refer to Appendix E)

Table 5-2. XMesh Packet Structure

Type	Name	Description	Component
uint16_t	addr	Destination address (next hop)	TinyOS Header (MICA2). The MICAz header has 5 additional bytes.
uint8_t	type	AM type; defines type of message	
uint8_t	group	AM group	
uint8_t	length	Remaining bytes in message, N/I CRC	
uint16_t	sourceaddr	Address of mote that sent the message	XMesh multihop header
uint16_t	originaddr	Address of mote that originated the message	
uint16_t	seqno	Message sequence number.	
uint8_t	socket	Application ID	
uint8_t	data	Payload	Payload size is set with the TOSH_DATA_LENGTH define. Default size is 29 bytes
uint16_t	crc	CRC check (Refer to Appendix E)	CRC

IMPORTANT: The maximum data size is typically limited to 55 bytes. Extending the data size increases SRAM usage due to creation of multiple TOS buffers.

Shorter data length messages can be sent at any time. `TOSH_DATA_LENGTH` only determines the maximum message size (see section 5.2.1).

5.2 XMesh Messaging API

XMesh can transfer messages **upstream** (from nodes to a base station) and **downstream** (from a base station to a node). Downstream communication enables efficient transmission of data from

the base station Mote to a node in the *XMesh* network. The downstream path is the same as the upstream path as determined by the upstream route taken by the packets from a node. A downstream message can only be sent if the base station Mote has previously received an upstream message from the mote.

IMPORTANT: For downstream communication the base station Mote must have received at least one upstream message from the node (data, health or any other type of upstream message).

Messages can be sent with two QOS (Quality of Service) levels:

1. **Link level acknowledgement:** This QOS provides transmission retries between a sender and receiver mote if an acknowledge message is not received by the sender. This QOS does not guarantee that a multihop message was successfully transmitted from the originator to the base station (or downstream). Using link level acknowledgement is the best QOS for low energy and is appropriate for systems that require the lowest energy and don't require 100% delivery of data.
2. **End-to-End acknowledgement:** This QOS combines link level acknowledges with an end-to-end acknowledge. For upstream messages the base station will return an acknowledgement to the originator. For downstream messages the base station will receive and acknowledge from the intended source. The *XMesh* API allows the user to determine if the message should be resent. This QOS consumes more power than just link level acknowledges and also consumes more of the RF bandwidth. Users can for any transmission, use either link level or end-to-end acknowledgement (with link level acknowledgement).

XMesh provides a set of TinyOS data and interfaces that allow users to wire TinyOS components and call them from their application. Users can do the following:

- Send upstream and downstream messages from the end point, with or without requiring end-to-end acknowledgement
- Intercept traffic for in-network processing such as data aggregation and distributed compression
- Snoop traffic for various promiscuous listening purposes

5.2.1 The MhopSend Interface (\MoteWorks\interfaces)

The `MHopSend` interface uses the application id to parameterize the commands. Users are highly encouraged to use this interface (as opposed to Send interface which is described below) to transmit packets. This interface includes the following 3 commands/events:

Example Wiring	`MyappM.MhopSend -> XMeshRouter.MhopSend[AP_ID];`
Example Usage	`call COMM.send(BASE_STATION_ADDRESS, MODE_UPSTREAM, dataMsgPtr, sizeof(dataMsg));`

Interface	`command void* getBuffer(TOS_MsgPtr msg, uint16_t* length);`
Description	Given a TinyOS message buffer, provide a pointer to the data payload section that an application can use as well as its length. If a protocol-unaware application is

sending a packet with this interface, it must first call `getBuffer()` to get a pointer to the valid data region. This allows the application to send a specific buffer while not requiring knowledge of the packet structure.

Parameter	Description
Msg	The message to get the data region of
Length	Pointer to a field to store the length of the data region.
Return	A pointer to the data region

Interface `command result_t send(uint16_t dest, uint8_t mode, TOS_MsgPtr pMsg, uint16_t length);`

Description Sends a message buffer with a data payload of a specified length

Parameter	Description
dest	Destination Mote_Id for the message. (Usually BASE_STATION_ADDRESS for upstream messages)
mode	MODE_UPSTREAM_ACK: upstream with return acknowledge, MODE_UPSTREAM: upstream no return acknowledge, MODE_DOWNSTREAM_ACK: downstream with return acknowledge MODE_DOWNSTREAM: downstream no return acknowledge MODE_ONE_HOP_BROADCAST: one hop broadcast.
pMsg	pointer to the buffer to be sent
length	The length of the data buffer sent using this component. **This must be less than or equal to the maximum length provided by getBuffer()**
return	Whether the send request was successful: SUCCESS means a sendDone() event will be signaled later, FAIL means one will not. This does not mean that the destination mote received the message, only that the message was transmitted.

Interface `command result_t send(TOS_MsgPtr msg, uint16_t length);`

Description This Send interface uses the AM type to parameterize the command. It is provided to maintain backward-comparability with previous *XMesh* applications that use AM type to distinguish different applications. **New applications should not use this interface.** Send will send a message buffer with a data payload of a specific length. The buffer should have its protocol fields set already, either through a protocol-aware component or by `getBuffer()`.

Parameter	Description
Msg	pointer to the buffer to be sent
length	The length of the data buffer sent using this component. This must be <= the maximum length provided by getBuffer()
return	whether the send request was successful: SUCCESS means a sendDone() event will be signaled later, FAIL means one will not. This does not mean that the destination mote received the message, only that the message was transmitted.

Interface `event result_t sendDone(TOS_MsgPtr msg, result_t success);`

Description Signals when a packet sent with `send()` completes.

Parameter	Description
Msg	pointer to the message sent
success	Whether the send was successful SUCCESS: the packet was transmitted and a link level acknowledge received. FAIL: no link level acknowledge was received after 6 transmit attempts. On the 7th attempt a new parent was selected but no acknowledge was received. The 8th attempt was a broadcast message.
return	Should always return SUCCESS

5.2.2 Receive() and ReceiveAck() Interface

This interface allows network end-points to receive a data packet or an acknowledge packet, without having to know about the internal structure of the packet or the layers below them in the stack.

Example Wiring	`MyappM.RcvAck -> XMeshRouter.ReceiveAck[appID];`
Example Usage	`event TOS_MsgPtr RcvAck.receive(TOS_MsgPtr pMsg, void* payload, uint16_t payloadLen)`

Interface

```
event TOS_MsgPtr receive(TOS_MsgPtr msg, void* payload,
uint16_t payloadLen);
event TOS_MsgPtr receiveAck(TOS_MsgPtr msg, void* payload,
uint16_t payloadLen);
```

Description These two interfaces share the same signature of command/event. The content of the payload is different.

Parameter	Description
msg	A pointer to the buffer received
payload	The payload portion of the packet for this protocol layer. If this layer has layers above it, it should signal receive() with payload incremented by the size of its header. Payload is a pointer into the msg structure.
payloadLen	The length of the payload buffer. If this layer has layers above it, it should signal receive() with payloadLen decreased by the size of its headers and footers.
return	The buffer to use for the next receive event

Interface

```
event result_t intercept(TOS_MsgPtr msg, void* payload,
uint16_t payloadLen)
event result_t snoop(TOS_MsgPtr msg, void* payload,
uint16_t payloadLen);
```

Description `intercept()`: Signals that a message has been received for the mote and the wired application ID (AP_ID).

`snoop()`: Signals any message overheard for the wired application ID (`AP_ID`).

These two interfaces share the same signature of command/event, the only difference between the two is that intercept handles the packet that is meant for the current mote, while snoop handles the packet that is **NOT** meant for the

current mote. **Note that these routines will only intercept/snoop messages for the application ID that they are wired to.**

Parameter	Description
msg	The complete buffer received
payload	The payload portion of the packet for this protocol layer. If this layer has layers above it, it should signal receive() with payload incremented by the size of its header. Payload is a pointer into the msg structure.
payloadLen	The length of the payload buffer. If this layer has layers above it, it should signal receive() with payloadLen decreased by the size of its headers and footers.
success	Indicates the packet should be forwarded, FAIL indicates that it should not be forwarded.

5.2.3 Promiscuous Listening

This interface allows the application to snoop all radio messages including broadcast messages regardless of the application id and address.

Example Wiring	`XMeshRouter.PromiscuousSniff -> MyappM.PromiscuousSniff;`
Example Usage	`event void PromiscuousSniff(TOS_MsgPtr pMsg)`

To use `PromiscuousSniff` include the following declaration in the `provides{}` section of the application module.

```
module XSnfM {
      provides {
          ……
          event void PromiscuousSniff(TOS_MsgPtr pMsg);
      }
```

5.3 Using the Messaging API

5.3.1 Active Messaging and Application ID

TinyOS has historically used an AM parameter in TOS messages as a service/application identifier. This allowed users to route messages to different services in their application. *XMesh* now reserves this parameter and it is not available to the user. *XMesh* supplies the same service through an Application ID. Application ID is used in the user application as the parameter of `MhopSend` interface, while AM type is used inside *XMesh* (radio layer, routing layer and transport layer). Application ID allows applications to multiplex to different user services with the same AM type.

User applications only deal with Application IDs through the `MhopSend/receive` interface to send and receive message. *XMesh* decides which AM type is appropriate for the message. AM type is internal to *XMesh*; currently there are 16 predefined AM types in *XMesh* that users should never use for other purposes. The most current defined types can be found in Appendix A.

⚠ **WARNING:** Do not use the AM parameter in multihop messages; this parameter is reserved by *XMesh*.

IMPORTANT: Application IDs from 128 to 255 are reserved by Crossbow for future use. The user's Application IDs should always be from 1 to 127.

When sending a message, the application should implement the following code:

1. Get a pointer to a data buffer, and typecast it to an application data structure, for example:

   ```
   pData = ( Ping_t *) call MhopSend.getBuffer(&gMsgBuffer,&Len));
   ```

   `pData` now points to the application payload portion of the TOS message, and Len has the length of the available payload buffer. The maximum data length is determined by the `TOSH_DATA_LENGTH` define.

2. Send the message. The value of `dest` and mode depends on the transportation mode.

   ```
   Call MhopSend.send(dest, mode, &gMsgBuffer, length);
   ```

	Upstream ack	Upstream no ack	Downstream ack	Downstream no ack
dest	Base	Base	Remote mote ID	Remote mote ID
mode	MODE_UPSTREAM_ACK	MODE_UPSTREAM	MODE_DOWNSTREAM_ACK	MODE_DOWNSTREM

`Base = BASE_STATION_ADDRESS`

NOTE: When calling the `MhopSend` interface to send packets, *XMesh* will decide the AM type for the message based on the mode parameter specified in the function call. The appropriate AM type will go into the type field of TOS header, and `appID` will go into the socket field of the `TOSMHop_Msg` header.

The base station will respond with an acknowledgement when it receives an upstream message that requires end-end acknowledgement. It is up to the application to determine whether to retransmit the message if no acknowledgement has been received.

5.3.2 Sending Upstream Messages

Applications simply call the send command:

```
call MhopSend.send(BASE_STATION_ADDRESS,MODE_UPSTREAM,&gMsgBuffer, sizeof(bfr));
```

and implement the `sendDone` event:

```
event result_t Send.sendDone(TOS_MsgPtr pMsg, result_t success) {return SUCCESS};
```

5.3.3 Sending Upstream Messages with End-End Acknowledgements

In order to receive the acknowledgement packet, the application needs to wire in:

```
AppM.RcvAck -> XMeshRouter.ReceiveAck[appID];
```

The `appID` should be the same as in the `MhopSend.send` wiring. Then the application implements the `ReceiveAck` event:

```
event TOS_MsgPtr RcvAck.receive(TOS_MsgPtr pMsg, void* payload, uint16_t payloadLen) {
      // here users can set the state to start sending next packet
 }
```

A common model is to start a one-shot timer after a message is sent out. If the end-end acknowledgement is not received before the timer expires then the application makes a decision as to whether to resend the packet. The recommended timer interval is 10 seconds for *XMesh-LP* and 20ms for *XMesh-HP*. A typical example is the following:

In a task (`sendTask`), send out the packet and start the timer:

```
if ((call Send.send(BASE_STATION_ADDRESS, MODE_UPSTREAM_ACK,&gMsgBuffer,
       sizeof(UpStream_t))) == SUCCESS) {
              call TimerAck.start(TIMER_ONE_SHOT, 20); //for high power stack
              bAckWait = TRUE;
           }
```

When the timer fired event occurs, decide whether to resend the packet based on a retry number:

```
           event result_t TimerAck.fired() {
                if ( NUM_RETRY != num_retry++) {
                    post sendTask(); }
                else { // reach retry limit
                      num_retry = 0;
                      bAckWait = FALSE; }
                      return SUCCESS;
                 }
```

If the end-to-end acknowledgement is received before the timer expired, cancel the timer:

```
event TOS_MsgPtr RcvAck.receive(TOS_MsgPtr pMsg, void* payload, uint16_t payloadLen)
       {
                if (bAckWait)  {
                call TimerAck.stop();
                num_retry = 0;
                bAckWait = FALSE; }
            return pMsg;
         }
```

NOTE: There is no global sequence number in *XMesh* (the sequence number in the *XMesh* multihop header is on a per hop basis, which is used for link quality computation), so the end-end acknowledgement does NOT carry a sequence number of the acknowledged packet. User applications should not send a new upstream acknowledgement packet if the ack for the previous packet is not received.

5.3.4 Sending Downstream Messages

There are two scenarios for sending downstream messages:

1. Sending directly from the base station mote.
2. Sending from a PC or other host that is connected to a base station Mote.

If sending from the base station mote, call the following send command:

```
call MhopSend.send(downstream_node_id, MODE_DOWNSTREAM, &gMsgBuffer, length);

//and implement the sendDone event:
event result_t Send.sendDone(TOS_MsgPtr pMsg, result_t success) { return SUCCESS; }
```

If downstream packets are sent from a PC or other host via a base station (MIB5xx plus MICA2 or MICAz) running *XMeshBase*, the PC code needs to:

- Put the downstream node id to the address field of the `TOSMsg` header
- Put 0x0C (downstream no ack) or 0x0E (downstream with ack) into the type field of the `TOSMsg` header
- Put the socket id into the socket field.
- Compute the crc (appendix E).
- **NEVER** modify the multihop header, which is internal to *XMesh. XMesh* (in the base station) will complete the remaining fields in the message before sending it downstream.

An example code is like this:

```
     Tos_msg.addr = downstream_id;
     Tos_msg.type = 0x0C; // sending downstream no ack
     Tos_msg.length = len;  //data length
     Tos_msg.socket = application_ID;  //application id to send message to
     Memcpy(&tos_msg.data, &app_data, len); //copy data into data section
    Tos_msg.crc = crc;                     //computed crc, Appendex E
    Send_to_serial(&tos_msg); //send the message to the serial port
      //this could send the message directly to UART or to a serial forwarder
```

5.3.5 Sending Downstream Messages with End-End Acknowledgements

If sending from the base station mote, call the following send command:

```
call MhopSend.send(downstream_node_id, MODE_DOWNSTREAM_ACK, &gMsgBuffer, length);

// and implement the sendDone event:
event result_t Send.sendDone(TOS_MsgPtr pMsg, result_t success) { return SUCCESS; }
```

If downstream packets are sent from a PC or other host via a base station (MIB5xx plus MICA2 or MICAz) running *XMeshBase*, the PC is the same as the previous example except for the type field:

```
Tos_msg.type = 0x0E; // sending downstream with ack
```

The PC code should also implement a callback for AM type 247, which is the end-to-end acknowledgement from the node to base station.

⚠ **WARNING:** Messages to and from *XMeshBase* require PPP-HDLX framing. Refer to Chapter 9 for details.

6 XMesh Route Controls

Sometimes users need to make application level decisions based on network conditions. To accommodate this need, *XMesh* provides a `RouteControl` interface (***MoteWorks/interfaces***) for the user's application to extract information from the routing component.

Example Wiring	`MyAppM.RouteControl -> XMeshRouter;`
Example Usage	`parent = call RouteControl.getParent();`

Interface `command uint16_t getParent()`

Description Returns the address of the present present. (0xffff for broadcast; i.e. no parent)

Interface `command uint16_t getDepth()`

Description Returns the node's depth. Depth is defined as how many hops away the mote is from the base station.

Interface `command uint16_t getSender(TOS_MsgPtr msg)`

Description Gets the address of the mote that sent the message.

Parameter	Description
`msg`	A pointer to the TOS_Msg of interest
`return`	The address of the sender

Interface `command uint8_t getOccupancy()`

Description *XMesh* queues up forwarding message. Returns the length of the routing forwarding queue, an indicator of how busy the current node is.

Interface `command uint8_t getQuality(uint8_t type);`

Description Gets a measure of goodness for the current parent. Returns value between 0-255 where 255 represents that 100% of messages has been heard.

type=1: `sendEst`

type=2: `receiveEst`

Interface `command result_t setUpdateInterval(uint16_t Interval);`

Description Sets the routing components internal route update interval.

Parameter	Description
`Interval`	The duration, in seconds, of successive routing updates.
`return`	SUCCESS if the operation succeeded

7 XMesh-LP (Low Power)

This chapter discusses *XMesh* in the Low Power mode. It will also discuss:

- What is Low Power Operation?
- Low Power Strategies

7.1 *Low Power Operation*

Processor Power Modes

XMesh motes can be configured to listen to radio messages in two modes; High Power (HP) and Low Power (LP). In High Power, the nodes that make up *XMesh* network are always on. The Mote's microprocessor and radio are continually on and consuming power. The radio is normally in the receive mode so that the Motes can listen to all neighborhood traffic at any time. This is the highest bandwidth mode for transmitting packets to the base station Mote.

A processor typically has several modes of operation that consumes different amounts of power. In the fully active mode, the processor consumes the maximum amount of power, which is typically in the 8 mA range. In the lowest power consumption mode, some form of deep sleep mode, the processor only consumes in the order of 15 µAmps.

The differences between the power modes are processor specific. Users should consult Atmel's ATmega128 manual for the MICA2, MICAz Motes and ATmega1281 manual for the IRIS Motes (http://www.atmel.com). Typically the lowest sleep mode will have no peripherals running and will only provide SRAM retention. Usually an external interrupt is required to wake the processor. In most applications the external 32 kHz clock is used as the source of the wake up signal.

In TinyOS, the application user is not actively aware of the power management. There are no longer any explicit power management calls provided by the OS that will put the processor into sleep. Instead, since TinyOS is an event driven OS with tasks as the unit of execution, the scheduler will put the processor to sleep once the task queue is empty.

The processing involved in determining the sleep mode is a series of checks on the activity of the processor peripherals. The power management module will ensure that the sleep mode set will be the lowest power mode that can still accommodate the correct operations of currently active peripherals. The designers of TinyOS decided that since this check will delay the sleep operation, the actual checks occur before the scheduler calls the sleep command. Thus, it is the responsibility of low level drivers to call the checks before and after using peripherals. For further detail consult the *scheduler.c* and *HPLPowerManagement.nc* source files.

Radio Power Modes

The radio transceiver typically has two modes of operation. It has a transmit state and a receive state. Depending on the specific radio transceiver, the TX (Transmit) and RX (Receive) operations consumes power in the range of 10 to 20 mA. In addition to TX and RX, the radio transceiver also has a series of low power states. When the transceiver is fully powered down, it consumes around 3 µW.

7.1.1 Low Power Strategies

Since the OS already takes care of the power management of the processor, the focus then shifts toward making communication less power intensive. It should be noted that most sensor network applications have very low data rates that do not require continuous processor or network activity. Any strategy that tries to reduce energy used by the radio should take advantage of the low duty cycle requirements of typical sensor network applications. However it is not enough just to power down the radio when it's not sending a message. A radio must also be able to receive messages from its peers and know when to power on the radio for reception.

Power Cycling

Some nodes in a network are known ahead of time to be edge devices that do not need to participate in routing. These devices can adopt the power strategy of powering on the radio when they need to communicate and then powering off when the transmission is completed (*XMesh-ELP*). This assumes that these edge devices will be able to make contact with a node that is capable of routing the message from the edge device through the network.

Power Cycling on a Known Schedule

This strategy involves power cycling the radio on a fixed interval by all nodes in a network. Every node using this strategy will periodically power on their radio to listen for activity. The listening time of a node is fixed and the interval between each channel monitoring is also fixed. The period between channel monitoring is known through out the network. Thus if any node wishes to communicate with its neighbors, it will transmit a wake up sequence for the duration of the wakeup period before transmitting the actual message. In this fashion if any neighboring nodes detect any radio activity during its channel monitoring, it will remain on until the message is completely received. This strategy allows nodes to power down a majority of the time and only power on during channel monitoring and message transaction.

Power Cycling on a Synchronized Schedule

In the previous strategy, every node in the network powers on their radio at a fixed periodic interval. If a node monitors the channel 8 times per second then the period is 125 ms between each channel monitoring. When a node wishes to send, the node must first send a wakeup sequence of 125 ms or however long this period is. This consumes a lot of energy for simply notifying its neighboring nodes. The reason the wakeup sequence must span the entire period is because nodes are not synchronized. Without synchronization nodes do no know the exact moment in the periodic interval when its neighbors will monitor the channel.

With a synchronized schedule where every node periodically monitors the channel during the same time window, then the wakeup sequence can be dramatically reduced. This time window, if in the neighborhood of 1ms, can guarantee that every node will monitor the channel for activity within 1ms of each other. Thus the wakeup sequence will only need to span 2 ms.

7.1.2 Performance Metrics of Low power techniques

Period Length

The amount of time between two consecutive channel monitoring operations. If a node is setup to monitor the channel 8 times per second then this length is 125ms.

Bandwidth

Since every node may only send or receive one packet per period, the bandwidth is thus determined by the length of this period. If the period is 125 ms, then the bandwidth is 8 packets per second.

Latency

The latency is determined by the duration of the listening period. If the duration is 125 ms, then that is the latency per link.

Monitoring Energy

The amount of energy every node must spend to periodically monitor for channel activity.

Transmission Energy: The amount of energy used for the transmission of every packet including the wakeup sequence.

Reception Energy: The amount of energy used for the reception of every packet.

7.1.3 Analysis of Low power techniques

Period Length vs. Bandwidth and Latency

The period length is directly proportional to the Latency and inversely proportional to the bandwidth. Increasing the period length will lower the bandwidth while increasing the latency

Period Length vs. Energy Consumption

The period length is inversely proportional to the monitoring energy. Thus increasing the period length will decrease the monitoring energy.

Period Length vs. Transmission and Reception Energy

The period length will only have an effect on transmission and reception energy when the listening periods are unsynchronized or if a packet need to be send sent out with a wakeup sequence that must span the entire period length.

The longer the period length is, the greater the wake up sequence must be to span the entire period length. If the receiver is assumed to be unsynchronized, then on average the receiver will power on during the middle of the period length. Thus the reception energy will all increase by only by half as much as the transmission energy on average.

7.1.4 Time Synchronized Radio Stack and the Periodic Wake up Checks

The radio stack uses the synchronized time clock which is provided by the Time Synchronization service (see Section 7.1.4), to schedule periodic wake-up checks for sensing RSSI. This is achieved by:

- A periodic wake-up check is initiated when the clock's lowest 7 bits all reads zeroed (0) or 128 ms. A timer event for each wake-up check must be scheduled as well.
- When a wake-up check needs to be scheduled, the radio stack requests the current time value. The number of clock ticks are counted until the lower bits read zero (0) and then a

calculation is made for future scheduled wake-up checks. This method allows the clock value to be moved forward and backward (in time) without causing the undue interruptions to the timer events.

- Prior to proper time synchronization, the node relies on the initial un-synchronized value of the timer, which results in periodic sampling at 128 ms intervals.

7.1.5 Radio Stack and Packet Transmissions

In addition to scheduling the wake-up check, the radio stack also schedules packet transmissions base on the synchronized clock. There are three types of packet transmissions:

- Full Extended Preamble
- Short Extended Preamble
- Standard Preamble

These various types of packet transmissions are used by the routing and time synchronization layer based on the recipient list.

The **Full Extended Preamble** is used to communicate with all neighboring nodes regardless of the presence of time synchronization. This packet transmission is scheduled to start transmitting 15 ms after the wake-up check so that the nodes that are properly synchronized with the transmission node incur minimal reception costs.

The **Short Extended Preamble** is used to communicate with time synchronized nodes. This packet transmission is scheduled to be transmitted precisely when the other nodes will perform their channel sampling. Nodes will detect the incoming transmission and have time to turn on their radios before the actual data packet begins to arrive.

The **Standard Preamble** is used to communicate with high-power nodes that leave their receivers on continuously. This packet transmission contains no extra preamble bytes and is schedule to transmit between the periodic wake-up checks. It can be transmitted without causing surrounding nodes to wake up.

The Table 7-1 describes the packet transmission type.

Table 7-1 Packet Transmission Types

Packet Type	Usage	Preamble Duration	Start Time	Strength Parameter
Full Extended Preamble	Neighborhood communication	140 ms	T = 15	0
Short Extended Preamble	Time sync communication	40 ms	T = 114	0xffff
Standard Preamble	Base station communication	0 ms (2ms)	T = 15	0x7fff

NOTE: The network stack uses the different packet transmission types depending on the value of their strength field in the outgoing packet.

The node's average power consumption can be calculated by determining the packet transmission type and the number of packets that were transmitted and received. The expected

lifetime of a node can be calculated by using the parameters for the RX cost, TX cost, and RF Wake-up check cost as well as the number of each type of packet that was sent and received.

8 XMesh-ELP (Extended Low Power)

This chapter discusses *XMesh* in the Extended Low Power mode. It will also discuss:

- What is ELP?
- *XMesh-ELP* interface
- Building *XMesh-ELP*
- Testing *XMesh-ELP*

8.1 What is ELP?

XMesh-ELP achieves the minimum operating power because motes spend almost all of their time in a sleep state. *XMesh-ELP* only works for nodes which are located at the edge of the network. These nodes do not forward radio messages upstream or downstream for other motes; i.e. they can only be the children of other motes and never the parents. The Figure 8-1 shows a graphical representation of the network topology.

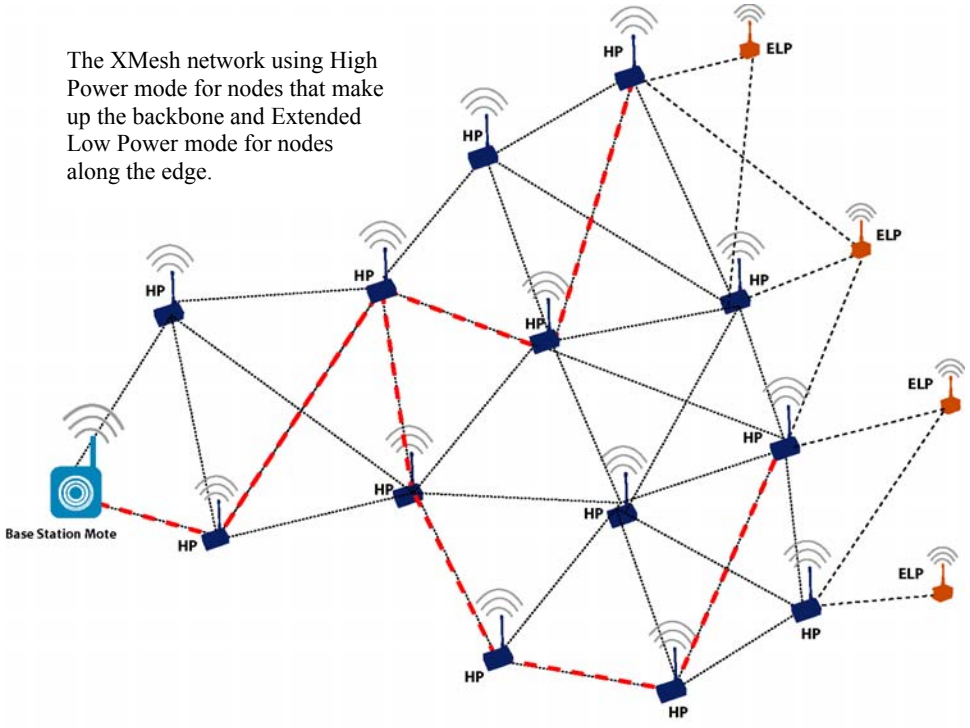

The XMesh network using High Power mode for nodes that make up the backbone and Extended Low Power mode for nodes along the edge.
HP
ELP
Base Station Mote

Figure 8-1. *XMesh-ELP* Network Topology

The ELP strategy is intended for applications were data is send very intermittently. These types of devices normally sleep for minutes to hours or perhaps days. Some examples of devices that could use ELP are:

- Light switches which only send messages several times per day. For this application the device must quickly wake-up and send the message.

- Battery operated machines that are only used several times a day. This type of application could require the machine to power-up and start a communication session for a period of time then go back to sleep.

ELP Motes join the mesh through the following:

- On power-up they will stay awake until they join the mesh. This means that they have located their parents.
- They can then go into the sleep state. The ELP node retains it's neighborhood table during sleep. The next time it wakes up it will use the same parent but if it's not successful it will try to use another parent from the table.
- They will periodically (user-defined) power-up and transmit a health message to the base station using end-end acknowledge. If they receive an acknowledgement they will go back to sleep. If no acknowledge is received the ELP node will try several times again before giving up.

ELP motes transmit route updates but advertise their cost as infinite which means that no other mote will pick them as a parent. ELP motes assume that the network topology regarding their parents is static. If the neighborhood experiences drastic changes (eg: all parents are turned-off) then the ELP mote will start a fast formation process to pick a new parent before it goes back to sleep. This generally means the ELP node will stay awake for 2-3 route update interval.

8.2 Operational Theory of ELP

On start-up the mote needs to join the mesh. This is done by calling `ElpI.route_discover(rui)`. The service will wait up to rui*(ROUTE_UPDATE_INTERVALS) to join the mesh. The event `ElpI.route_discover_done(success, parent)` signals the result: if success is TRUE, then the ELP node has successfully joined the mesh and parent parameter contains the ID of the parent. If success is FAIL, the node has failed to join the mesh and parent contains broadcast address. And the user needs to decide whether to try again or sleep.

After the mote has joined the mesh the `ElpI.sleep()` can be invoked. While the node is in ELP sleep mode, health packets are periodically (interval specified by the user) sent to the base station and with an expected acknowledgement from the base station. If the acknowledge does not return within a set time it will try again, with up to `iRetries`. After the `iRetries`, it will return a `sleepdone()` with failed and not try again until `ElpI.sleep()` is called again. If an acknowledgement is received then the service will stop *XMesh*, start a timer (health interval) and put the radio to sleep. After the health interval, the ELP node will wake-up and send another health packet, waiting for an acknowledgement. It uses the same timeout strategy as previously described. After the duration time interval has elapsed the `sleepDone` event will be issued (with SUCCEED) with the radio powered on.

This service can optionally go into the sleep mode with or without sending the initial health packet. The parameter `force_sleep` is used to control this behavior; if it is set to 1, the ELP node will go to sleep immediately after `ElpI.sleep()` is called, without sending the initial probing health packet; if it is set to 0, the ELP node first sends a health packet to the base and

won't sleep until the acknowledgement is received. Note that in either case the node will send health packets to the base station periodically and will do `iRetries` if no acknowledgement is received.

⚠ **WARNING:** ELP motes can only receive downstream messages if they stay awake which increases their power consumption. Users can develop a strategy where the ELP Mote wakes, sends an upstream message requesting messages from the base station.

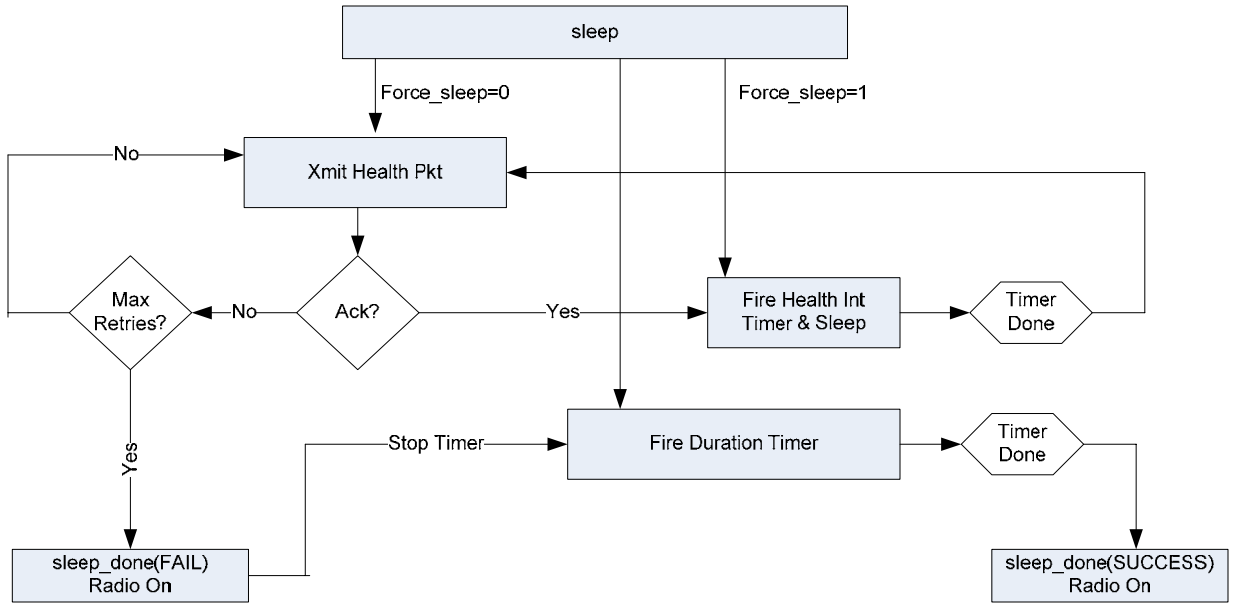


Figure 8-2. ELP Logic Flow Chart

The Figure 8-3 shows the sequence of events for `force_sleep` = 0:

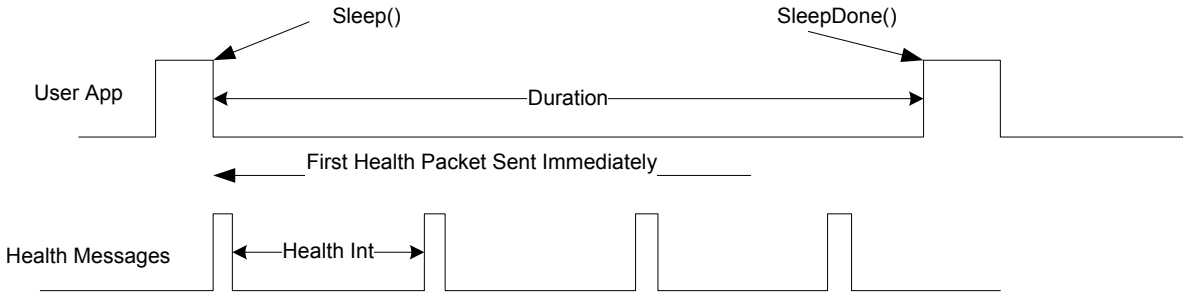


Figure 8-3. Sequence of Events during ELP

8.3 The XMesh ELP Interface

There are two interfaces (***MoteWorks/tos/interfaces***) to control *XMesh-ELP* enabled Motes.

- ElpControlI
- ElpI

8.3.1 ElpControlI Interface

Example Wiring	`MyappM.ElpControlI -> XMeshRouter.ElpControll;`
Example Usage	`call ElpControll.enable();`

Interface `command result_t enable()`

Description Enables the ELP mode – in this mode the mote will periodically wake and send health messages to the base as determined by the `sleep()` command below.

Interface `command result_t disable()`

Description Disables the ELP mode

Interface `command bool isActive()`

Description Query if the node is in ELP mode

8.3.2 Elpl Interface:

Example Wiring	`MyappM.Elpl  -> XMeshRouter.Elpl;`
Example Usage	`Call Elpl.wake();`

Interface `command result_t route_discover(uint8_t rui);`

Description Attempts to join the mesh. When called it:

Turns the radio on for up to rui (ROUTE_UPDATE_INTERVALs) attempting to find a parent.

If a parent is found, sends a health message (retries up to x times) requiring an end-end acknowledge from the base station.

Parameter	Description	Typical Values
`rui`	The number of ROUTE_UPDATE_INTERVALS to wait for joining the mesh (i.e. within this time the mote should have heard 2 route updates from neighbors and selected a parent)	3

Interface `event result_t route_discover_done(uint8_t success,uint16_t parent);`

Description Event returns after `route_discover` has either found a parent or timed out after the rui period. If `route_discover` fails it's up to the application to decide when to try `route_discover` again.

Parameter	Description
`success`	SUCCESS: A parent has been found FAIL: No parent was found
`parent`	The address of the parent.

Interface `command result_t sleep(uint16_t duration, uint16_t health_interval,uint8_t iRetries, uint8_t force_sleep);`

Description Puts an *XMesh-ELP* capable mote to sleep.

NOTE: Also disables UART0 during the sleep time.

Parameter	Description	Typical Values
`duration`	Sleep duration for the radio(sec). At the end of this interval the application is signaled (sleep_done) to perform whatever tasks it needs to do (such as taking data and transmitting the result). NOTE: this only puts the radio to sleep. The mote can still execute any application required tasks.	30 minutes
`health_interval`	Time between sending health packets (sec). This time determines how often the mote makes sure that it is still part of the mesh. Increasing the time interval will reduce power consumption. Health_interval should be shorter than Duration.	5 minutes
`iRetries`	Number of times to transmit a health packet and get an acknowledgement. If the acknowledge fails the sleep_done event will be returned with success=FAIL and the node will stay awake until the next call to sleep.	5
`force_sleep`	If force_sleep=zero a health packet is generated immediately after the command is executed and every health_interval during the duration interval. If force_sleep=one then health packets are not generated until after one health_interval.	0

Interface `event result_t sleep_done(result_t success);`

Description Event signaled every time the node wakes from the sleep interval.

The radio and UART0 will wake up when the next message is sent or by issuing a

`wake()` command (see below).

NOTE: the radio is not on at this time.

Interface `command result_t wake();`

Description Wakes a node from sleep into a full power state and turns the radio and UART0 on. When this completes a `wake_done()` will be signaled.

Interface `event result_t wake_done( result_t success);`

Description Signaled after node leaves ELP mode. Always returns SUCCESS.

8.4 Building XMesh-ELP

The application needs to follow the ELP coding requirements for the mote to work properly in ELP mode. Typical usage of ELP by the user would be:

An external interrupt wakes-up the user's application. The application calls `ElpI.wake()` which turns the radio on and rejoins the mesh.

```
    async event result_t FireDetect.alert( ) {
           call ElpI.wake();          // turn on the radio and rejoin the Mesh
     }
```

The application waits until `ElpI.wakedone()` and then sends radio messages.

```
    event result_t ElpI.wake_done(result_t ss){
            call MhopSend.send(…);
           }
```

After the radio message has been sent the application calls `ElpI.sleep` to return to sleep mode.

NOTE: `ElpI.sleep()` returns SUCCESS if the mote has returned to ELP sleep mode.

```
event result_t Send.sendDone(TOS_MsgPtr pMsg, result_t success) {
   call ElpI.sleep(elp_sleep_sec,elp_health_sec,elp_retry,monitor_flag);
   return SUCCESS;
}
```

8.5 Testing XMesh-ELP

A test application for ELP mode is supplied in ***MoteWorks/apps/examples/TestElp2***. This application will:

- Start-up in full power.
- Send route updates and monitor route updates until it joins the mesh.
- Send a health packet to the base station requesting a downstream acknowledge.
- Go to sleep for 20 seconds.
- Repeat the previous two steps continually.

Building the Application:

1. To build the application for a MICAz type

   ```
   make micaz route,elp
   ```

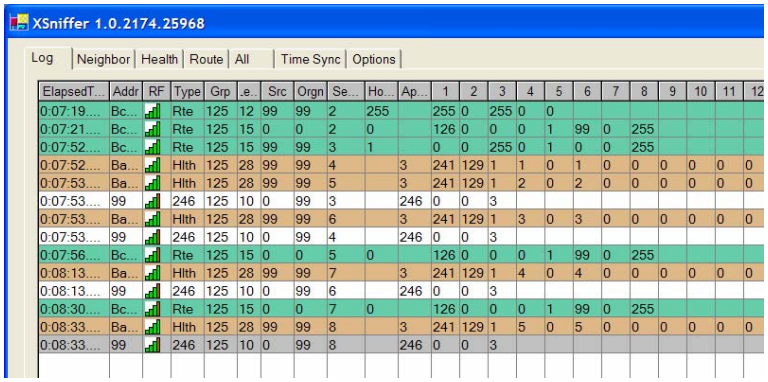
2. Program this into a mote.
3. Build the *XMeshBase* (Chapter 9) application (route,hp base) and program into the base station mote.
4. Build and load *XSniffer* with the same radio frequency.
5. Run the base station on batteries or a MIB programming board.
6. Run *XSniffer* (refer to Chapter 11).

IMPORTANT: The ROUTE_UPDATE_INTERVAL in the *Makefile.Component* for both the ELP application and *XMeshBase* must be the same.

8.6 Monitoring the Network with *XSniffer*

The following screen shot shows the *XSniffer* Log page during the startup of the network

1. During the initial phase the ELP Mote has not joined the network. At this time it does not have a parent as seen by its route update message at 0:07:19. The mote current during this time is around 26 mA.
2. At 0:07:21 seconds the base station broadcasts a route update (Rte) notifying the ELP mote that it is seen.
3. At 0:7:52 seconds the ELP mote broadcasts its route update (Rte) and has joined the network selecting the base station as a parent and it sends health packets.
4. Health packets are sent every 20 seconds.



ElapsedT...	Addr	RF	Type	Grp	.e..	Src	Orgn	Se...	Ho...	Ap...	1	2	3	4	5	6	7	8	9	10	11	12
0:07:19....	Bc...		Rte	125	12	99	99	2	255		255	0	255	0	0							
0:07:21....	Bc...		Rte	125	15	0	0	2	0		126	0	0	0	1	99	0	255				
0:07:52....	Bc...		Rte	125	15	99	99	3	1		0	0	255	0	1	0	0	255				
0:07:52....	Ba...		Hlth	125	28	99	99	4		3	241	129	1	1	0	1	0	0	0	0	0	0
0:07:53....	Ba...		Hlth	125	28	99	99	5		3	241	129	1	2	0	2	0	0	0	0	0	0
0:07:53....	99		246	125	10	0	99	3		246	0	0	3									
0:07:53....	Ba...		Hlth	125	28	99	99	6		3	241	129	1	3	0	3	0	0	0	0	0	0
0:07:53....	99		246	125	10	0	99	4		246	0	0	3									
0:07:56....	Bc...		Rte	125	15	0	0	5	0		126	0	0	0	1	99	0	255				
0:08:13....	Ba...		Hlth	125	28	99	99	7		3	241	129	1	4	0	4	0	0	0	0	0	0
0:08:13....	99		246	125	10	0	99	6		246	0	0	3									
0:08:30....	Bc...		Rte	125	15	0	0	7	0		126	0	0	0	1	99	0	255				
0:08:33....	Ba...		Hlth	125	28	99	99	8		3	241	129	1	5	0	5	0	0	0	0	0	0
0:08:33....	99		246	125	10	0	99	8		246	0	0	3									

Figure 8-4. Screenshot displaying *XSniffer* Output

IMPORTANT: If the JTAG fuse (Appendix B) is not disabled the sleep current will be less than 3 mA.

9 XMeshBase

This chapter discusses *XMeshBase* which is the standard base station application *XMesh*. The topics reviewed are:

- What is *XMeshBase*?
- *XMeshBase* services
- How to build *XMeshBase*

9.1 What is XMeshBase?

All *XMesh* networks require a base station which acts as a gateway for a PC, Stargate or other client to interface with the *XMesh* network. Base stations consist of a MICA2 or MICAz (**not a MICA2DOT**) running *XMeshBase* and mounted on one of the following Crossbow interface boards:

1. MIB510 using a RS232 serial port interface to the client.
2. MIB520 using a USB port to interface to the client.
3. MIB600 using an Ethernet port to interface to the client.
4. Directly mounted to a Stargate with a serial port interface.

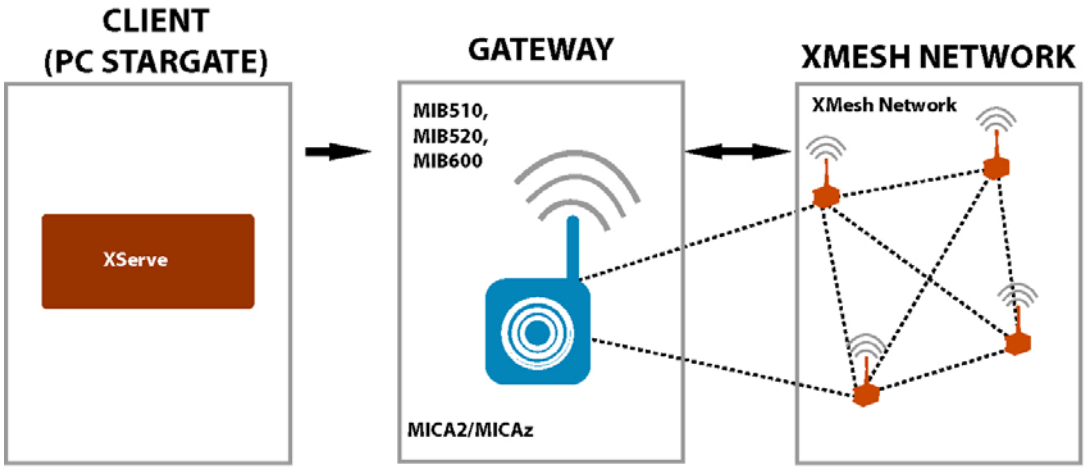


Figure 9-1. Mesh Networking Architecture

Usually the client runs *XServe*, Crossbow's server interface to the base station, but users can directly communicate to the mesh via the base station. The interface between the base station Mote and the MIB or Stargate is a serial RS232 or TTL interface. It uses a standard serial protocol for communication.

9.2 XMeshBase Services

XMeshBase provides the following services:

1. It is the seed mote that forms the *XMesh* network. It outputs route messages that inform all nearby motes that it is the base station and has zero cost to forward any message.
2. For downstream communication *XMeshBase* automatically routes messages down the same path as the upstream communication from a mote.
3. It is compiled with a large number of TinyOS message buffers to handle more children than other motes in the network.
4. It forwards all messages upstream and downstream from the client using a standard serial framer protocol.
5. *XMeshBase* can periodically send a heartbeat message to the client. If it does not get a response from the client within a predefined time it will assume the communication link has been lost and reset itself.

9.2.1 Serial Protocol

The base station communicates with the host through a serial bus at a baud rate of 57,600 bps. The incoming and outgoing packets are framed using a PPP-HDLX protocol (http://www.faqs.org/rfcs/rfc1662.html). In *XMeshBase* this is handled by the `FramerM` TinyOS component. The format of the packet is:

- The raw data packet is wrapped on both ends by a frame synchronization byte of **`0x7E`**. This is used to detect the start and end of a packet from the stream.
- The raw data packet uses an escape byte of **`0x7D`**. This is needed in case a byte of payload data is the same as a reserved byte code, such as the frame synch byte **`0x7E`**. In such a case, the payload data will be preceded by the escape byte and the payload data itself will be exclusively OR'ed with **`0x20`**. For example, a payload data byte of **`0x7E`** would appear in the data packet as **`0x7D 0x5E`**.
- On a Windows XP machine, multiple byte values are byte-swapped in the data stream. For example, the 2 byte UART Address field (**`0x007E`**) will appear as **`7E 00`** in the byte stream.

The Table 9-1 describes the raw data packet.

Table 9-1. Raw Data Packet Structure

Sync 0x7E	Type 0x42	Data TOS_Msg Header	Data Payload	CRC 0xAFE2	Sync 0x7E

Byte #	Field	Description	
0	Ssynch byte	Always 0x7E	
1	Packet Type	Type	Description
		P_PACKET_NO_ACK (0x42)	- User packet with no ACK required.
		P_PACKET_ACK (0x41)	– User packet. ACK required. Includes a prefix byte. Receiver must send a P_ACK response with prefix byte as contents.

Byte #	Field	Description	
		P_ACK (0x40)	– The ACK response to a P_PACKET_ACK packet. Includes the prefix byte as its contents.
		P_UNKNOWN (0xFF)	– An unknown packet type.
2…n-1	Payload Data	In most cases will be a TinyOS Message of varying length, which is described below.	
n	SYNC_BYTE	Always 0x7E	

9.3 Building XMeshBase

XMeshBase is located in the ***/Moteworks/apps/XMesh/XMeshBase*** directory.

To build the application run the following command from the application directory:

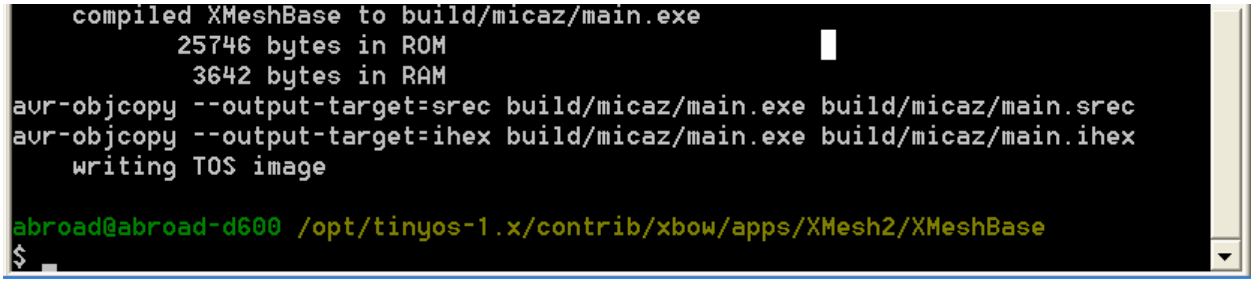
`make <hardware platform> base route,hp` for *XMesh-HP* or *XMesh-ELP*

`make <hardware platform> base route,lp` for *XMesh-LP*

IMPORTANT: Before building the application make sure the correct build parameters are set in the build make files (Chapter 2). If the ROUTE_UPDATE_INTERVAL has been changed from the default value make sure that *XMeshBase* and the application are using the same values in the *Makefile.Component*.

XMeshBase's TinyOS message data size must be equal or greater to the application message size. The default message size for *XMeshBase* is 55 (see *Makefile.component*). If the application data packets are larger than 55 data bytes then build *XMeshBase* with `TOSH_DATA_LENGTH` > 55.

As can be seen from the following Cygwin screen *XMeshBase* will use about 3600 bytes (out of 4096 bytes) of SRAM. This is due to the increased buffers allocated for the base station. Since no user application runs on the base station this will not be a problem.



To program the compiled code into the mote (MICA2 or MICAz):

`make <mote platform> reinstall,0 mib510|mib510|mib600, <device location>`

IMPORTANT: The base station is always programmed with node ID equal to zero.

9.4 Using the Heartbeat

XMeshBase provides the link from the mesh network to the outside world. It is important that this link does not fail. To monitor the health of *XMeshBase* a heartbeat mechanism is incorporated to validate that the link between the base and the PC is operating correctly. The heartbeat mechanism sends a heartbeat packet from the base station over the serial port every 5 seconds. Applications running on the PC can monitor the packets to verify that they arrive. If *XMeshBase* fails to send a heartbeat the monitoring application can alert users that a problem has occurred with *XMeshBase* connection.

For users using *XServe* with *XMeshBase*, a complete monitoring solution has already been incorporated. *XServe* monitors heartbeats from *XMeshBase*. If three heartbeats are missed *XServe* alerts users of the failure. For applications using the MIB510 or MIB520 programming board for their base station, *XServe* will also attempt to restart the *XMeshBase* application by power cycling the Mote.

The heartbeat messages sent by the *XMeshBase* application have the structure described in Table 9-2

Table 9-2. Packet Structure of *XMeshBase* Heartbeat Messages

Data Fields	Description
`uint16_t addr`	This the Tos_Msg address field which is always set to 0
`uint8_t am_type`	This is the Tos_Msg am_type field. The am_type for heartbeat messages are 0xFD
`uint8_t group`	This is the Tos_Msg group field set to the built group id for XMeshBase
`uint8_t length`	This is the Tos_Msg length field. The length of the heartbeat message is 2 bytes.
`uint16_t seq_no`	This is the heartbeat sequence number. It's a 16 bit number which wraps around after overflow. The sequence number is useful for applications which want track the packets though the most important aspect of the heartbeat is its absence.

The heartbeat application is turned on by default in *XMeshBase*. To remove the heartbeat functionality from *XMeshBase* comment out the following line in the *Makefile*.

```
CFLAGS += -DFEATURE_HEARTBEAT
```

To monitor heartbeats start *XServe* with the following flag:

```
-heartbeat=<num missed>
```

The <num missed> variable is the minimum number of heartbeats missed before *XServe* will attempt to restart *XMeshBase*. Each heartbeat period is 5 seconds, so in the case of a serial connection problem the base station will be down for <num missed>*5 seconds.

10 XMesh Services

The *XMesh* services include the following features:

- Health Statistics
- Time Synchronization for Low Power
- OTAP
- WatchDog

10.1 Health Statistics

Health statistic packets allow the user to monitor the health of the *XMesh* network. They are enabled or disabled from the user's application. If enabled they are transmitted upstream to the base station. These packets contain useful information about how well the Mote is performing in the mesh regarding radio traffic. Information such as battery voltage and the current parent's RSSI is also included.

10.1.1 Enabling Health Packets

XMesh exports a command called `health_packet` that enables health packet reporting during run time:

```
command void  health_packet(bool enable, uint16_t interval);
```

if enable is TRUE, the health packet will be sent out periodically every interval seconds. Interval is usually set to several minutes in order not to impact the overall mesh message rate. Typical values for interval are:

- *XMesh-HP* : 1 minute or more
- *XMesh-LP* : 10 minutes or more

☑ EXAMPLE

(also refer to ***/MoteWorks/apps/examples/XMeshCountsToLeds***)

```
// In the App.nc wiring file add:
     AppM.health_packet -> XMeshRouter;
//In AppM.nc, the user can enable the health packet reporting:
// in the AppM.nc uses{ section add:
      command void health_packet(bool enable, uint16_t intv);
// in the AppM.StdControl.start section add:
      Call health_packet(TRUE, 600);  // 10 minute interval
//This will disable the health packet reporting:
      Call health_packet(FALSE,0);
```

The base station will forward these packets along with other data packets to *XServe* for data conversion, and then they can be relayed to *MoteView* for monitoring. They can also be viewed with *XSniffer* (see Chapter 11)

10.1.2 Data Packet – Health Header

There are two types of health packets in *XMesh*:

- Statistics Health Packets
- Neighbor Health Packets

The two health packets are transmitted sequentially (in an alternative fashion, one every health update interval) and use the same packet format. All health packets use AM type 3 (see Appendix A)

All Health packets have a similar header component which describes the information contained within the health packet.

Table 10-1. Statistics Health Packet Structure

Data Fields	Description
`uint8_t type_node`	This is for backward compatibility. The value of the first 4 bits for XMesh2 will always be 0xF. Any other value means this is an XMesh1 health packet.
`uint8_t version`	Most significant bit: 0 = high power mesh; 1 = low power mesh.. Least 3 significant bits: 0 = XMesh 1 version of health packet. 1 = XMesh 2 version of health packet
`uint16_t type`	The value of this field indicates if the packet is a statistics packet or a neighbor packet. Statistic packets have a type of 0x01 and neighbor packets have a type of 0x02

10.1.3 Data Packet – Statistics Health Packet

Statistical health packets contain statistical information about the packets being sent through the particular node. The following types of data are sent in this type of packet:

- Accumulating packet counter (`num_node_packets`, `num_fwd_pkts`, `num_drop_pkts`, `num_rexmits`) represent statistical information on packet transmissions from the node gathered since boot time.
- Instantaneous power information such current voltage readings and accumulated power usage in low power.
- Current parent id and information such as link quality and rssi value.

The statistics health packet fields are provided in Table 10-2.

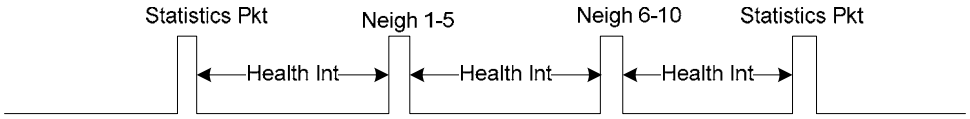
Table 10-2. Statistics Health Packet Structure

Data Fields	Description
`uint16_t seq_num`	This is the sequence number of the health packet.

uint16_t **num_node_pkts**	Number of application packets that have been generated locally.	
uint16_t **num_fwd_pkts**	Number of radio packets that the mote has forwarded in the mesh.	
uint16_t **num_drop_pkts**	Number of radio packets that the mote has dropped due to failed link level retransmissions.	
uint16_t **num_rexmits**	This is the number of times that the message was re-transmitted.	
uint8_t **battery_voltage**	Battery reading.	
uint16_t **power_sum**	Power statistics in low power radio stack (not used)	
uint8_t **rsvd_app_type**	Reserved Crossbow field to identify sending application.	
hn_quality **nodeinfo**	A record containing information about the link to the present parent	
	uint16_t **node_id**	Parent's ID
	uint8_t **link_quality**	Link quality to parent
	uint8_t **path_cost**	The routing path cost to the base station
	uint8_t **radio_link_indicator**	rssi or lqi value of the parent

10.1.4 Data Packet – Neighbor Health Packet

The Neighbor health packet contains information about the Mote's neighborhood and radio link quality to these motes. Motes track up to sixteen neighbors. Health packets can only send back information on five neighbors at any one time. If the table contains more than five neighbors the information is contained in sequential neighbor packets. If there is only a parent and no other neighbors the Neighbor health packet is not sent. These are still alternated with the statistics packets. The diagram below shows the sequence of health packets for a mesh with 10 neighbors in the neighborhood list.



The format for the neighborhood health packets is provided in Table 10-3.

Table 10-3. Neighbor Health Packet Structure

Data Fields	Description	
uint8_t **type_node**	This field is in the Health header. The bottom 4 bits will contain the number of neighbors sent in the packet.	
hn_quality **nodeinfo**	Records containing information about the link quality of the neighbor. Each record consist of the following elements:	
	uint16_t	Neighbor's ID

Data Fields	Description	
	`uint8_t`	Link quality normalized to 255 (100%). 100% indicates that both the neighbor and mote hear 100% of each other's messages.
	`uint8_t`	Hop count of the neighbor
	`uint8_t`	The RSSI or LQI value of the neighbor

10.2 Over-the-Air-Programming (OTAP)

The Over-the-Air-Programming (OTAP) feature allows users to reprogram any Mote within the *XMesh* network. OTAP allows one or more Motes to receive new programming images from *XServe* (via *XOtap*, a server-side application via wireless communication.

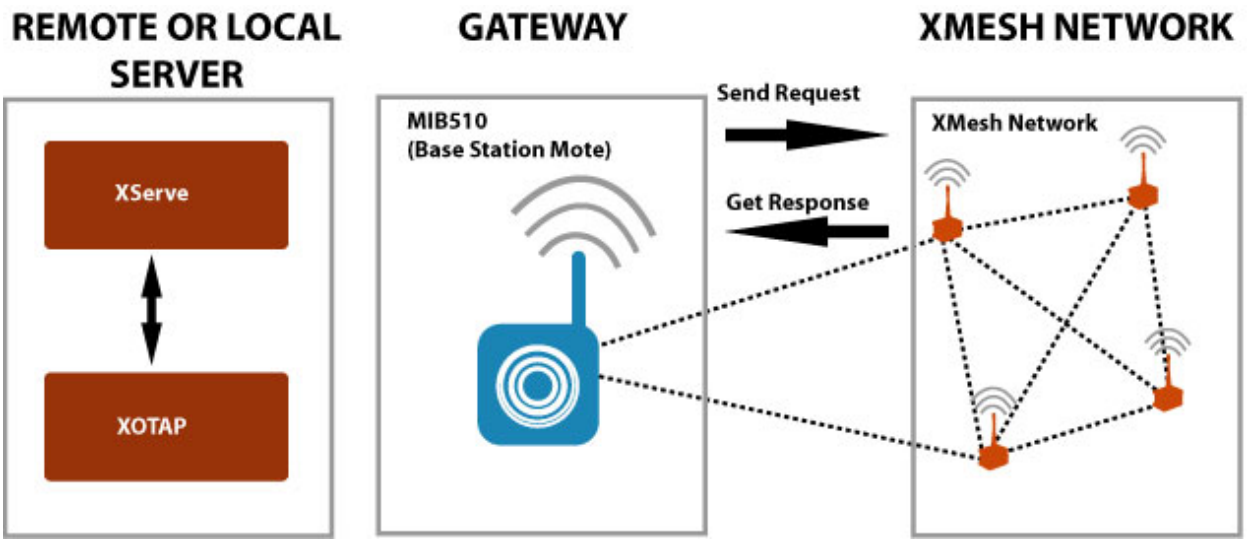


Figure 10-1. *XOtap* Architecture

10.2.1 How does OTAP Work?

Every Crossbow Mote has an external serial flash memory interfaced to the microprocessor. This memory can hold up to 512 kB of data and is non-volatile (i.e. retains its contents if no power is present). OTAP uses this memory to store code. It divides the serial memory into 4 slots (0, 1, 2 & 3) to hold different code/data images. Each slot can be a user-configured number of pages in 2k byte steps. By default each slot is 128 kB (or 64 pages) wide. Unused slots are available to the user for data logging.

Slot zero always holds the OTAP image. This is the full OTAP loader that must be invoked to download new code. Users can wire the OTAP components directly into their application however these components consume several hundred bytes of RAM. Instead Crossbow advises users to use small component, `XOTAPLiteM`. This component uses just 30 extra bytes. If an Application wires in *XMesh* component, the `XOTAPLiteM` is automatically available. The server can send a command to `XOTAPLiteM` which will then cause the Mote to reboot into the OTAP image from slot zero to do the full code download. The other slots in the memory are allocated

for user code or data. Before reprogramming, users must ensure that the OTAP image resides in slot zero of the serial flash memory.

OTAP works by transmitting small code fragments, down to a selected Mote. The entire code image is broken up into these fragments. As OTAP receives the fragments it will store them in the serial flash. The downloading sequence is independent of the reprogram and reboot process. Once code images have been stored in serial flash users can reboot to any image at any time.

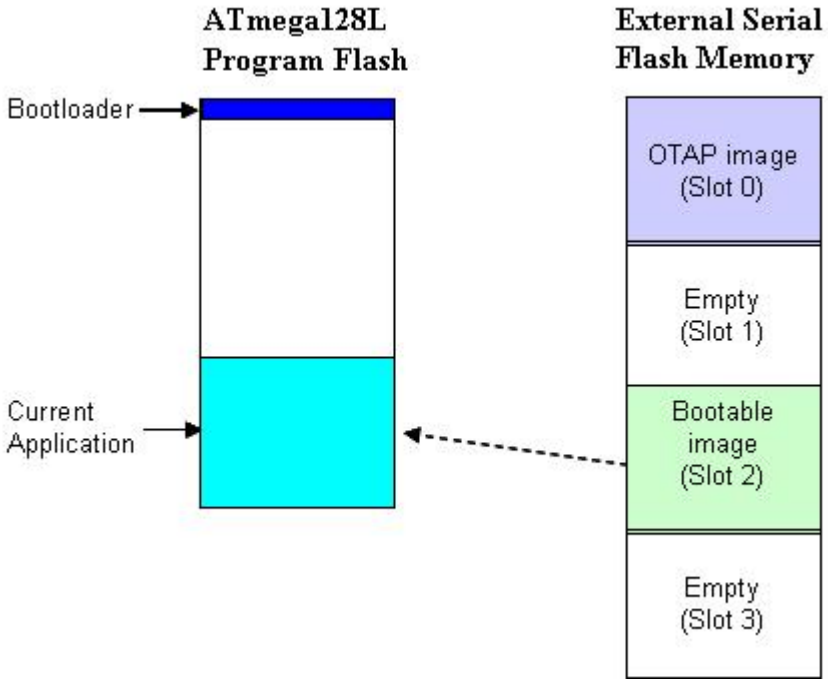


Figure 10-2. OTAP image transfer

Reprogramming the microprocessor from serial flash requires that bootloader code resides in the top part of the ATmega microprocessor's flash memory. This code is loaded once during the initial programming of the Mote via UISP.

There are several components required to run OTAP:

- *Bootloader*: The piece of code that is guaranteed to execute after each reset of the mote, independent of the TinyOS application.
- *XOTAPLiteM*: A sub-component wired into the user's application by including *XMesh* in the Mote.
- OTAP code image in slot zero of serial flash.
- *XServe* running on the server.
- *XOtap* running on the server.

The OTAP functionality is implemented within TinyOS by a component known as `XMgmt`. This component is responsible for storing the state of the images in the serial flash, responding to any queries from the *XOtap* tool and de-fragmenting program or data images sent from the server.

10.2.2 XOTAPLiteM

The `XOtapLoader` programmed can be wired into the user's application as follows: In the Application component file, add the following wiring:

```
implementation {
      ……
           ……
   MyAppM.XOtapLoader -> MULTIHOPROUTER;
}
```

In the Application module file add the following component interface and the command:

```
module MyAppM {
    provides {
              …
…;
    }
    uses {
        …
    interface XOtapLoader;
        …
}
```

Also add the command response command to check with the application if it can be interrupted before rebooting to another image. If the application is in the middle of a state, it can properly complete its actions and leave the mote in a known state before resetting:

```
event result_t XOtapLoader.boot_request(uint8_t imgId) {
  call XOtapLoader.boot(imgId);
  return SUCCESS;
}
```

Once the mote receives the boot command and the application gives a go-ahead on the reboot, it will schedule the reboot time based on how far away it is from the base, in other words, the closer it is to the base, the longer it should delay for the reboot, so that children won't lose pending downstream messages due to the reboot of their parents. The Table 10-2 shows the delay time for the reboot.

Table 10-2. Delay times for reboot

Hop_count	Delay (sec)
≥ 5	2
4	4
3	6
2	8
1	10

10.2.3 Bootloader

The Bootloader is an independent piece of code that is guaranteed to execute after each reset of the Mote, independent of the TinyOS Application. It is responsible for loading the program image into the Processor program flash memory if commanded prior to the reset by the *XOtap* tool's message.

The bootloader binaries for MICAz, MICA2, MICA2DOT and IRIS are maintained in the following directory:

/MoteConfig/TOSBootLoader/{bl_micaz.sec, bl_mica2.srec, bl_mica2dot.srec, bl_m2110.srec, bl}

The command to program the bootloader is the following (all as one line):

```
uisp -dprog=mib510 -dserial=/dev/ttyS0 --wr_fuse_h=0xd8 -dpart=ATmega128 --
wr_fuse_e=ff --upload if=bl_micaz.srec
```

You may need to choose appropriately the parameters for serial port, mote programmer and the pathname to bootloader binary.

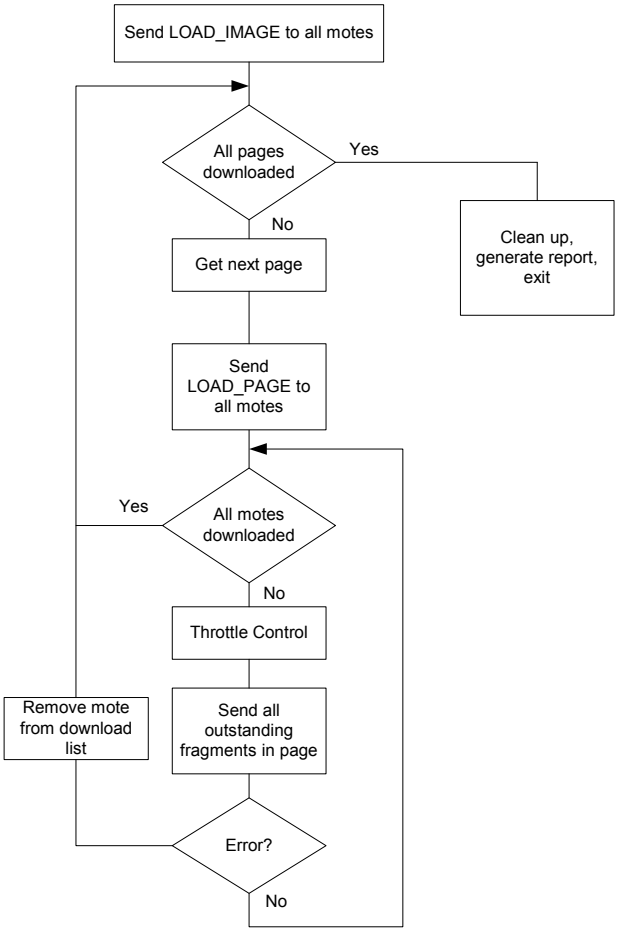
⚠ **WARNING:** The UISP will erase the bootloader every time the Mote is programmed so it must always be reloaded every programming cycle. Also make sure that the correct fuse settings are used (`--wr_fuse_h=0xd8`, `-wr_fuse_e=ff`)

10.2.4 OTAP Protocol

The OTAP protocol reformats a large code image into pages and fragments in order to reduce the traffic required for the download process. The downloaded image is broken into pages and fragments that fit in a TinyOS packet. A fragment is the amount of the image that can be transmitted in a single TOS packet, i.e. 19 bytes (29-byte TOS message with 7 byte *XMesh* header and 3 bytes OTAP header). A page is a sequential set of fragments that are managed as an entity. There can be a maximum of 128 fragments per page.

A program image of 31,568 byes for example would be fragmented as:

1. 31568/19 = 1662 fragments (with round off)
2. 1662 fragments / 128 = 12 pages of 128 fragments and 13th page with 126 fragments.



10.2.5 OTAP Download Packet Format

The OTAP download packet contains the fields described in Table 10-3.

Table 10-3. OTAP Packet Fields

Field	Length (Number of Bytes)	Description
Image Id	1	This is the slot in the serial flash – between 0... 3.
Fragment	2	This is the fragment id of the fragment being transmitted.
data	19	This is the binary data for the fragment.

NOTE: The OTAP packet does not contain any page information. The page containing a fragment is determined by dividing the fragment offset by 128 (offset >> 7).

10.2.6 Promiscuous Listening

During an image download, the Motes in the download list will listen "promiscuously" for download packets and read fragments to update the image in the designated slot, even if the fragment is addressed to another Mote. When it is their turn to download fragments, the OTAP

algorithm will determine what fragments in the current page have been received and will only send missing fragments.

Whenever any OTAP download starts, *XOtap* first informs all the nodes in the list to be programmed to be ready to receive an "image" in the specified slot. Then it informs all the nodes in the list that it is going to send a specified page. After that, starting from the first node in the list, it sends downstream packets of data. All nodes which can hear this packet will "promiscuously" listen to this packet and update their slot.

10.2.7 XOtap Application

The *XOtap* application is a server side tool that works, either with *XServe* or directly connected to the serial port of the *XMesh* Gateway, to communicate with the *XMesh* network. It resides in the *XServe* Layer (in a remote or local server or Stargate) of the *XMesh* Network landscape. You use *XOtap* to download program images to the Motes by having the application first read an IHEX image file name and a list of Motes to download. Then the image is downloaded to each Mote. The application then writes a report and exits.

There are 3 basic types of OTAP commands:

1. Query - Gets status, loaded and boot images information
2. Load - Load program image or data
3. Boot - Boots into the specified image.

XOtap supports the following arguments described in Table 10-4.

Table 10-4. *XOtap* Command Arguments

Command Interface	Description
`-f <image_file>`	Download the file.
`-i <image_number>`	Image number
`-q`	Query the Mote status
`-v <threshold>`	Download if the voltage is above the threshold (default 2.7v)
`-p <image_number>`	Boot the image number.
`-sf <ip:port>`	XServe host/port (default to localhost:9001)
`-c <COM port>`	Serial port if connected directly (eg. -c COM1)
`moteID [moteID…]`	List the Motes to download or check status.

☑ EXAMPLE

10.2.8 OTAP Preparation using MoteConfig Utility

Before you can program the Motes in the network over the air, you need to prepare them with bootloader and OTAP image. You can use *MoteConfig* GUI utility to accomplish this. Follow these steps to prepare the Motes for over the air programming.

1. Start the *MoteConfig* from **Start>Programs>Crossbow>MoteConfig**

2. From **Settings>Interface Board Settings...** select appropriate programming interface board and port

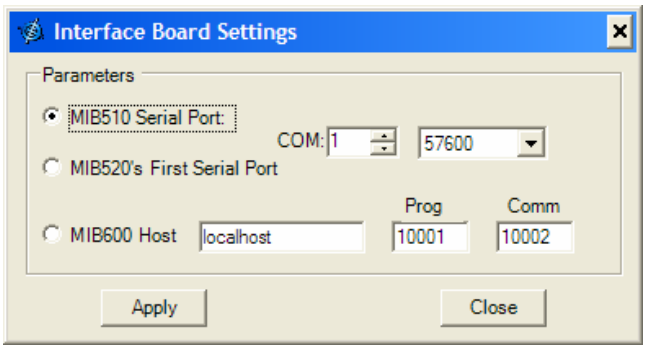


Figure 10-3. Programming Interface Board Settings in *MoteConfig*

3. OTAP enabled programming using UISP – Click on the **Local Program** tab and click on **Select.** Browse to an *XMesh* application file (main.exe). Choose appropriate **Mote ID**, **Group ID**, **RF Power**, **RF Channel** and make sure that **OTAP Enable** box is checked. Click on **Program**.

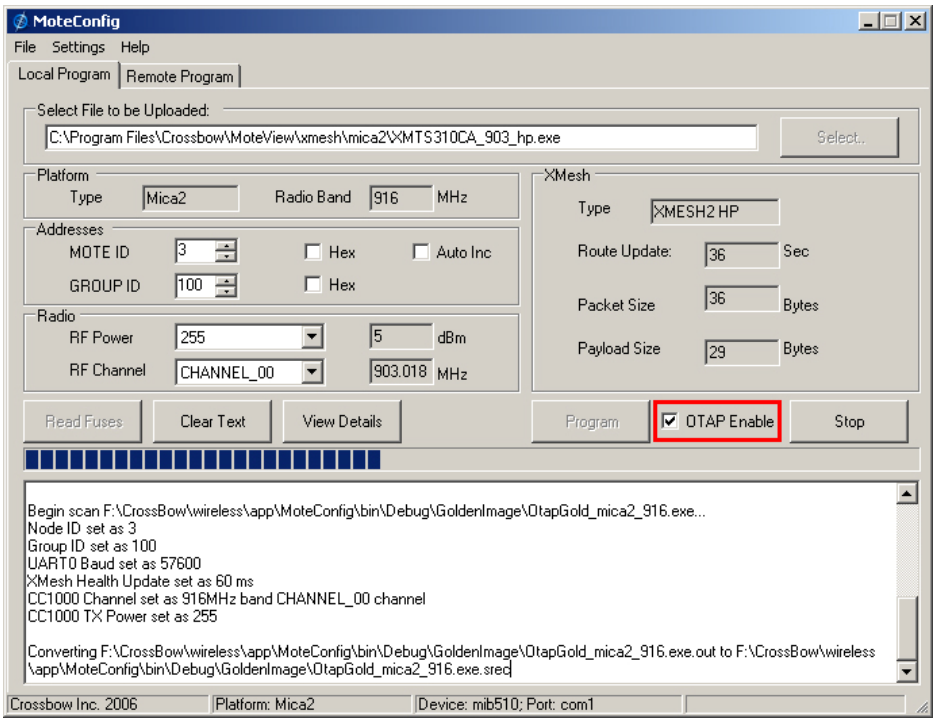


Figure 10-4. Programming *XMTS310CA* OTAP-enabled application using *MoteConfig*

4. Repeat the Step 3 for all the nodes in the network. When the bootloader is installed successfully, the LEDs count up twice when the node is switched on.
5. Program base station Mote with *XMeshBase* application, Mote ID = 0 and **OTAP Enable** unchecked.

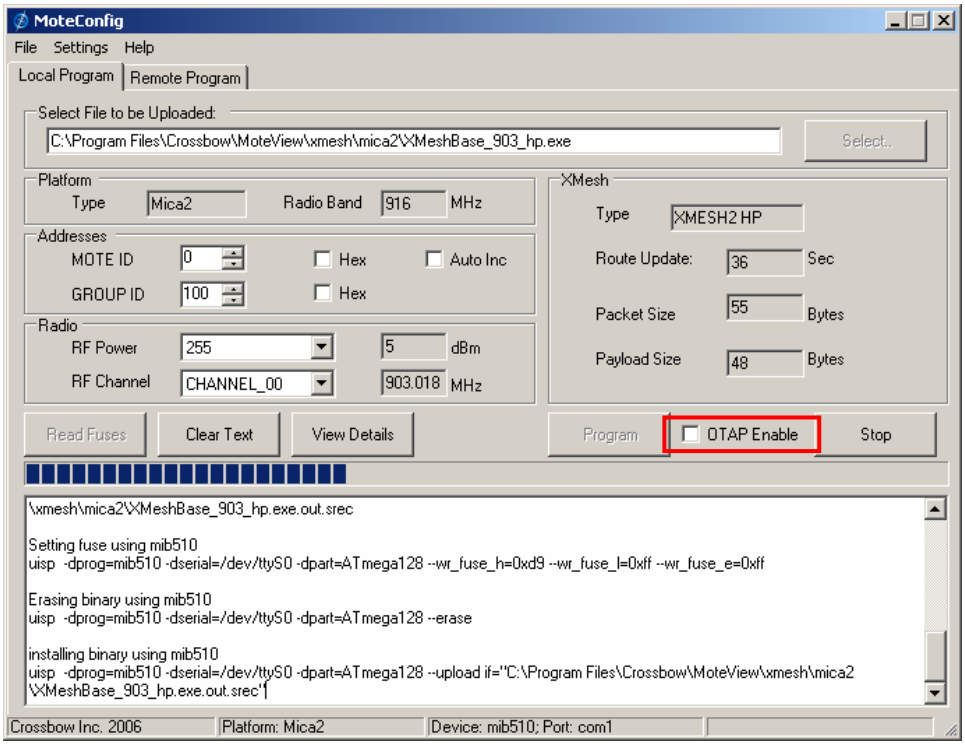


Figure 10-5. Programming *XMeshBase* application into base station using *MoteConfig*

10.3 OTAP using *MoteConfig* Utility

Once all the Motes are prepared for OTAP, you can then program them over the air. The following steps explain how to use MoteConfig to program the nodes in the network.

1. Connect the base node to the PC interface board and turn on the remote nodes that were prepared as shown in section 10.2.8.

2. Switch to the **Remote Program** tab.

3. Click on the **Search** button to start up *XServe* and listen for remote nodes. The *Motes* found within the network will be displayed in the tree-view control as shown in Figure 10-6.

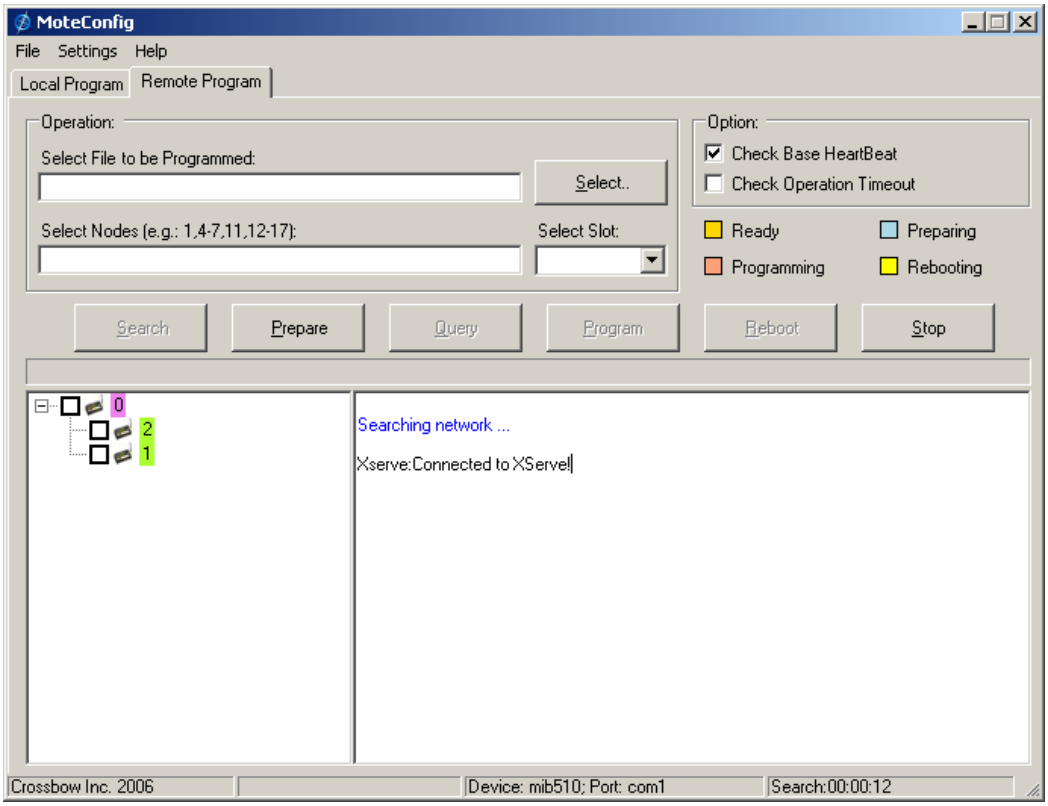


Figure 10-6. Searching for nodes within the mesh network.

NOTE: The base node will periodically blink with a magenta background. This indicates that heartbeat packets sent by the base firmware are being received by the PC. This verifies that the base station has been correctly configures.

4. The Motes can now be rebooted to the OTAP image (OtapGold.exe) by selecting nodes from the tree-view control and pressing the **Prepare** button. Nodes can also be selected by entering their IDs into the **Select Nodes** textbox. During this process, the **Prepare** button will be disabled and the selected node will turn blue.

NOTE: The node IDs entered in the **Select Nodes** textbox override the node selection in the tree-view control.

When the nodes have rebooted into the OTAP image, their background color will turn gold as shown in Figure 10-7.

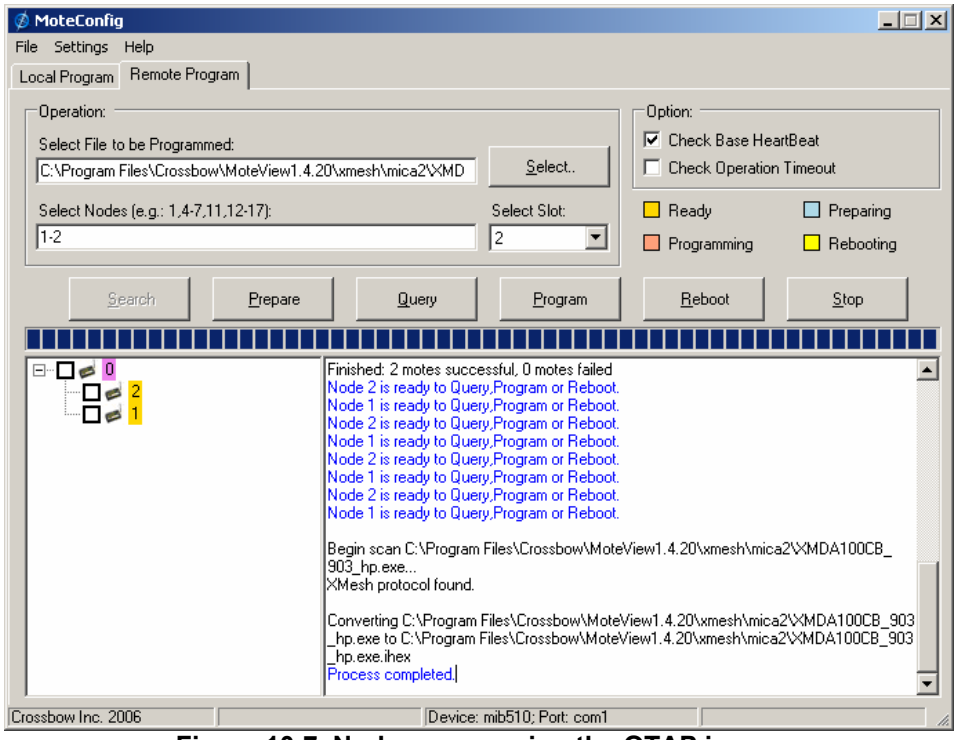


Figure 10-7. Nodes are running the OTAP image

5. **Query** – Users can optionally query a node when it is running the OTAP Image to get information about different slots as shown in Figure 10-8.

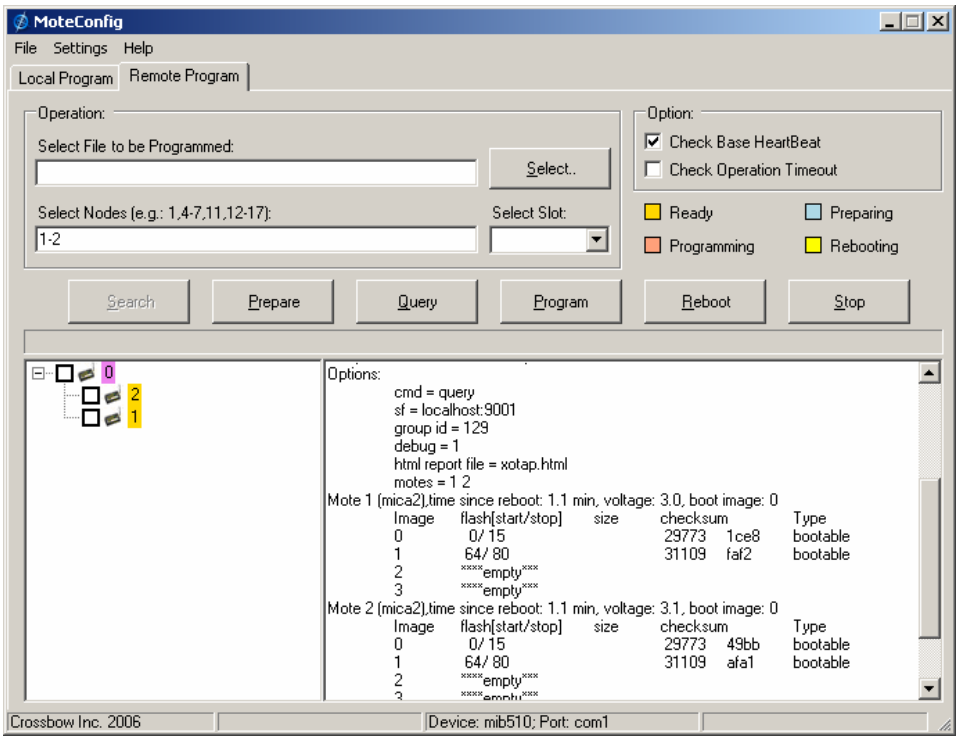


Figure 10-8. Querying the Nodes in the Network for OTAP Image

6. **Program** – Click on **Select** and browse to the binary image of the *XMesh* application (main.exe) that you want to program with. Check the nodes you want to program and specify the slot where you want to store the application. Alternatively, you can type the node IDs in **Select Nodes** box. Click on **Program** as shown in Figure 10-9. As the OTAP progresses, you will see the report in terms of number of pages downloaded into the flash. During the OTAP process, the color of the selected nodes turns to Orange as shown in Figure 10-10.

⚠ **WARNING:** You cannot write over the Slot 0, because it is reserved for the OTAP Image.

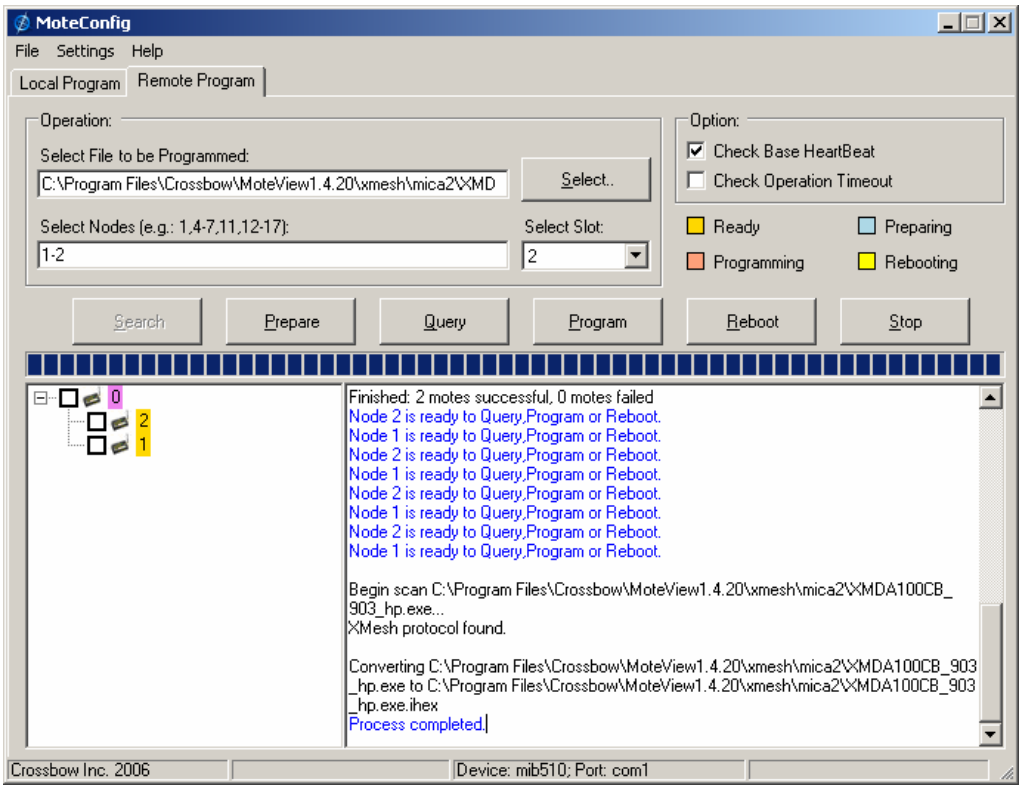


Figure 10-9. Select an Application for Programming the Nodes

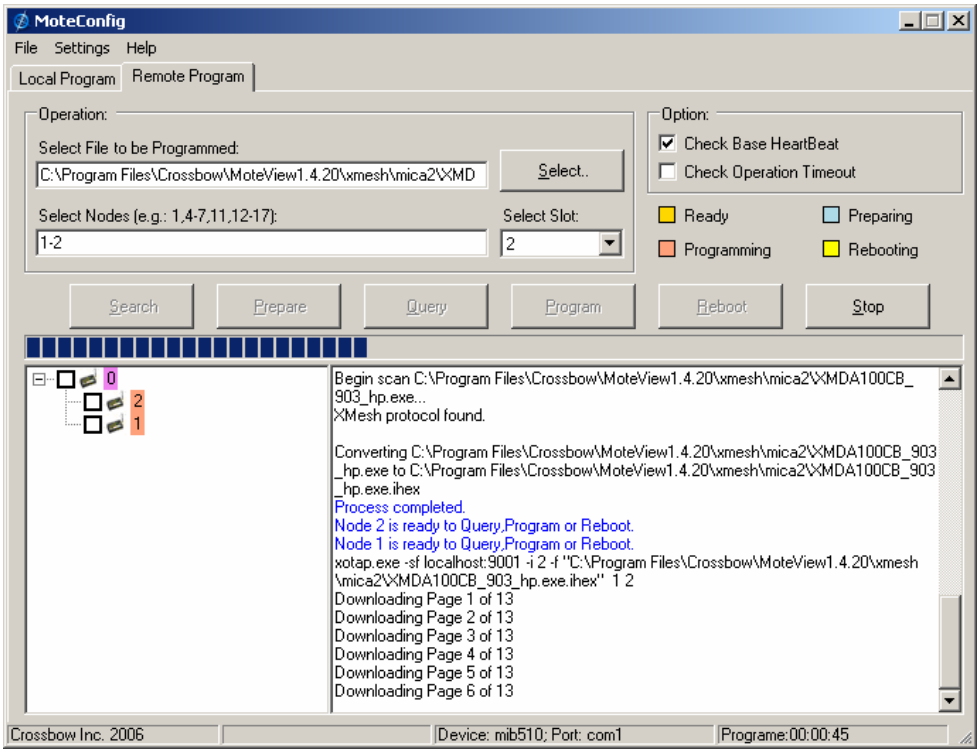


Figure 10-10. Programming the nodes in the network via XOTAP

Open the **Process Messages** window (by clicking on *File > View Process Details…*) to trace all downloading steps as shown in Figure 10-11. . When all the selected nodes are successfully programmed, the color of the selected nodes turns back to gold.

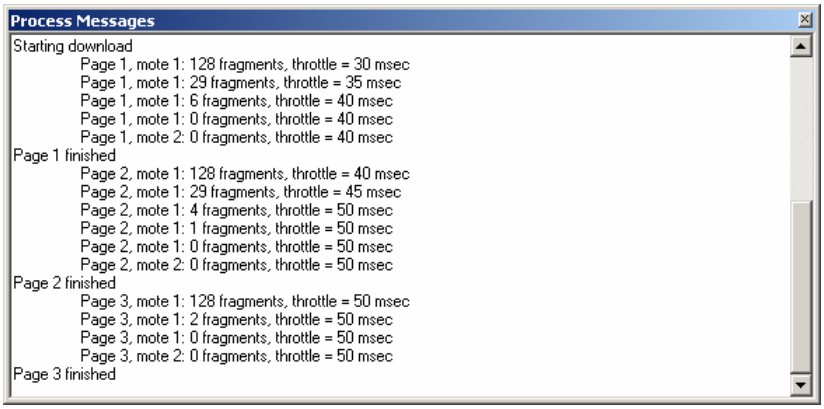

Process Messages
Starting download
Page 1, mote 1: 128 fragments, throttle = 30 msec
Page 1, mote 1: 29 fragments, throttle = 35 msec
Page 1, mote 1: 6 fragments, throttle = 40 msec
Page 1, mote 1: 0 fragments, throttle = 40 msec
Page 1, mote 2: 0 fragments, throttle = 40 msec
Page 1 finished
Page 2, mote 1: 128 fragments, throttle = 40 msec
Page 2, mote 1: 29 fragments, throttle = 45 msec
Page 2, mote 1: 4 fragments, throttle = 50 msec
Page 2, mote 1: 1 fragments, throttle = 50 msec
Page 2, mote 1: 0 fragments, throttle = 50 msec
Page 2, mote 2: 0 fragments, throttle = 50 msec
Page 2 finished
Page 3, mote 1: 128 fragments, throttle = 50 msec
Page 3, mote 1: 2 fragments, throttle = 50 msec
Page 3, mote 1: 0 fragments, throttle = 50 msec
Page 3, mote 2: 0 fragments, throttle = 50 msec
Page 3 finished

Figure 10-11. Trace all downloading steps

7. **Reboot** – The last step is to reboot into the newly loaded image for the selected nodes. To do this, check the nodes you want to reboot, specify the Slot and click on **Reboot**. Alternatively, you can type the node IDs in **Select Nodes** box. When all the selected nodes are successfully rebooted, you will see the output shown in Figure 10-12 and the color of the selected nodes turns back to Green.

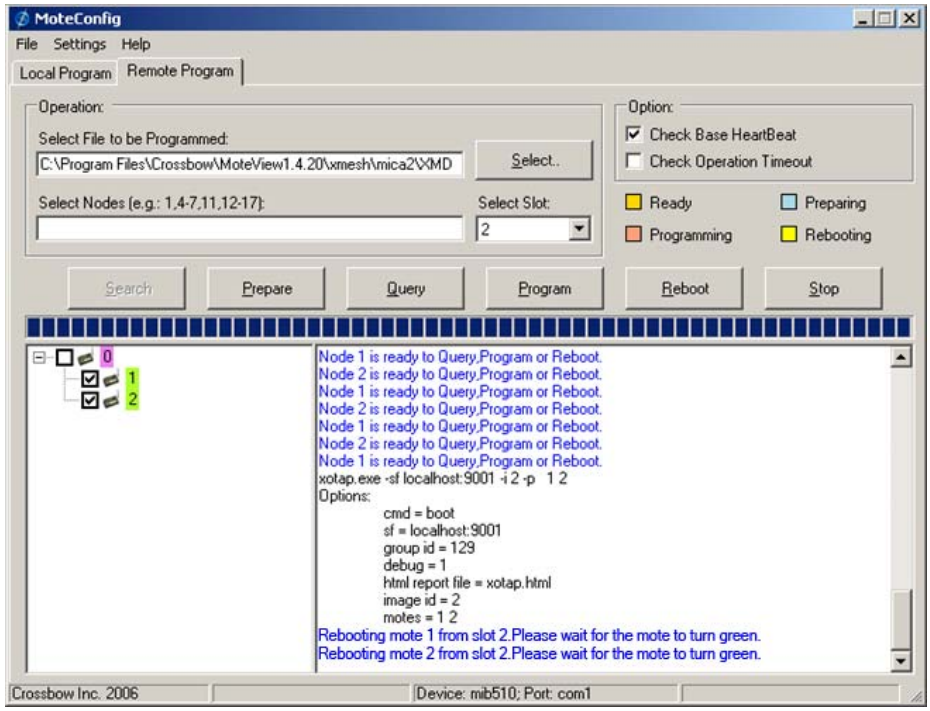


Figure 10-12. Rebooting the Nodes in the Network

The specified nodes should now start running the new application.

10.3.1 OTAP Using Cygwin Interface

For the users who prefer to Cygwin command line interface, the following section describes step-by-step procedure for the OTAP. The Users can also implement these command line arguments while developing their own client GUI.

1. Connect the base station to the PC interface board and turn on the remote nodes that were prepared as per Section 10.2.8.
2. Start *XServe* on the PC connected to the base station (assuming the base station is connected to COM3)

   ```
   $ ./xserve -s=/dev/ttyS3
   ```

3. Initialize - The next step in the OTAP process is to reboot all chosen nodes to OTAP Image for preparation of OTAP'ing a new image.

   ```
   $ ./xotap.exe -sf localhost -i 0 -p 1 2
   Options:
           cmd = boot
           sf = localhost:9001
           group id = 129
           debug = 1
   ```

```
        html report file = xotap.html
        image id = 0
        motes = 1 2
Rebooting mote 1 with image 0
Rebooting mote 2 with image 0
2 of 2 motes done
Finished: 2 motes successful, 0 motes failed
```

4. Query - Users can optionally query a node when it is running the OTAP Image to get information about different slots.

```
$ ./xotap.exe -sf localhost -q 1 2
Options:
        cmd = query
        sf = localhost:9001
        group id = 129
        debug = 1
        html report file = xotap.html
        motes = 1 2
Mote 5 (micaz),time since reboot: 2.6 min, voltage: 2.8, boot image: 0
        Image   flash[start/stop]       size    checksum        Type
        0         0/ 14                  28175  fada    bootable
        1        64/ 79                  28843  1350    bootable
        2       ****empty***
        3       ****empty***
Mote 15 (micaz),time since reboot: 2.7 min, voltage: 2.9, boot image: 0
        Image   flash[start/stop]       size    checksum        Type
        0         0/ 14                  28175  5b90    bootable
        1        64/ 79                  28843  b21a    bootable
        2       ****empty***
        3       ****empty***
2 of 2 motes done
Finished: 2 motes successful, 0 motes failed
```

5. Program - Specify the nodes you want to program and specify the slot. Select the binary image of the app (main.ihex). As the OTAP progresses, you will see the report in terms of number of pages downloaded into the flash.

⚠ **WARNING:** You should never write over the Slot 0, because it is reserved for the OTAP Image.

```
$ ./xotap.exe -sf localhost -i 2 -f
../../../apps/xmesh/XMTS310/build/micaz/man.ihex 1 2
Options:
        cmd = download
        sf = localhost:9001
        group id = 129
        debug = 1
        html report file = xotap.html
        image id = 2
        file = ../../../apps/xmesh/XMTS310/build/micaz/main.ihex
        flash offset = 128
        bootable = 1
        min voltage = 2.7
        throttle = 15
        motes = 1 2
Mote 1 (micaz),time since reboot: 4.2 min, voltage: 2.8, boot image:
none
Mote 2 (micaz),time since reboot: 4.2 min, voltage: 2.9, boot image:
none
Binary conversion complete, size = 28843 (12 pages, 1519 fragments)
Starting download
Downloading Page 1 of 12
…
…
        Page 11, mote 2: 0 fragments, throttle = 15 msec
Page 11 finished
Downloading Page 12 of 12
        Page 12, mote 2: 111 fragments, throttle = 15 msec
        Page 12, mote 1: 0 fragments, throttle = 15 msec
        Page 12, mote 2: 0 fragments, throttle = 15 msec
Page 12 finished
All pages downloaded
Registering image 2 on mote 1
Registering image 2 on mote 2
Download finished
2 of 2 motes done
Finished: 2 motes successful, 0 motes failed
```

6. Reboot - The last step is to reboot into the newly loaded image for the selected nodes. When all the selected nodes are successfully rebooted, you will see the output shown below.

```
$ ./xotap.exe -sf localhost -i 2 -p 1 2
Options:
        cmd = boot
        sf = localhost:9001
        group id = 129
        debug = 1
        html report file = xotap.html
        image id = 2
        motes = 1 2
Rebooting mote 1 with image 2
Rebooting mote 2 with image 2
2 of 2 motes done
Finished: 2 motes successful, 0 motes failed
```

The specified nodes should now start running the new application.

10.4 Watch Dog

XMesh uses a watchdog component (*WDTM.nc*) to perform a watchdog reset after it has missed 5 route update messages in a row. To enable this functionality, add the following line in the *Makefile*:

```
DEFINES += -DUSE_WATCHDOG
```

Once the watchdog functionality is enabled, the mote will reboot itself if it does not hear any route update message in a period of 5*RUI (Route Update Interval).

⚠ **WARNING:** Enabling the watchdog timer will increase the sleep current by an additional 15uA for the ATmega128.

IMPORTANT: Never enable watchdog on an ELP node, otherwise the ELP node will keep rebooting itself since it will miss most of the Route Update Message from its neighbors.

10.5 Time Synchronization for Low Power

The Time Synchronization service is used to establish a global network time stamp and to schedule network communication. Time synchronization is implemented on top of the long-preamble (Full Extended Preamble) communication mechanism that allows nodes to efficiently communicate before the synchronization process is complete. However, once synchronized, all transmissions are based on the globally time synchronous framework, which provides:

- An implemented time synchronization protocol that is based on the system clock signal from the base station Mote and distributed to each node in the network.
- Periodically, each node will broadcast its version of the current time along with its Authority Rating.

The Authority Rating is represented as an 8-bit unsigned integer. When a time sync message is received, a node will do the following:

1. Set its time clock to the value contained in the packet if the authority value is lower than its current value.
2. Set its authority value to two greater than the authority value of the packet.
3. Every time a node transmits a packet, the node will increment its authority value by one.
4. If the authority value of an incoming packet's authority value is equal to the node's existing value, then the time value is adopted only if the source's sequence number is less than the receiving node's ID.

NOTE: The zero (0) is the highest possible authority value and is assigned to the base station.

When a node transmits a time synchronization packet, it first initiates the transmission. The radio communication stack fires a timing event to the Time Synchronization Layer when the start symbol transmission begins. The Time Synchronization Layer reads the current clock value and writes it into the packet as it is transmitted.

Concurrently, the authority value of the packet is set to 350 until the time values of the packet are inserted into the packet. This is to ensure that data is updated inside the packet before transmission. If, for some reason, the timing values are not inserted into the bytes containing the time reading before it is updated, the low authority value will cause other nodes to ignore the transmission. The time value is transmitted as a 64-bit integer with the least significant unit representing 1024^{th} of a second (~1 ms).

The time synchronization service causes nodes to synchronize to the time value that reaches them in the shortest number of hops. In the event that a link is broken and the node must receive a synchronization message that has traveled with more hops, the node will wait two extra cycles before accepting the new updated path. This time synchronization method also considers all equal length paths as equally accurate.

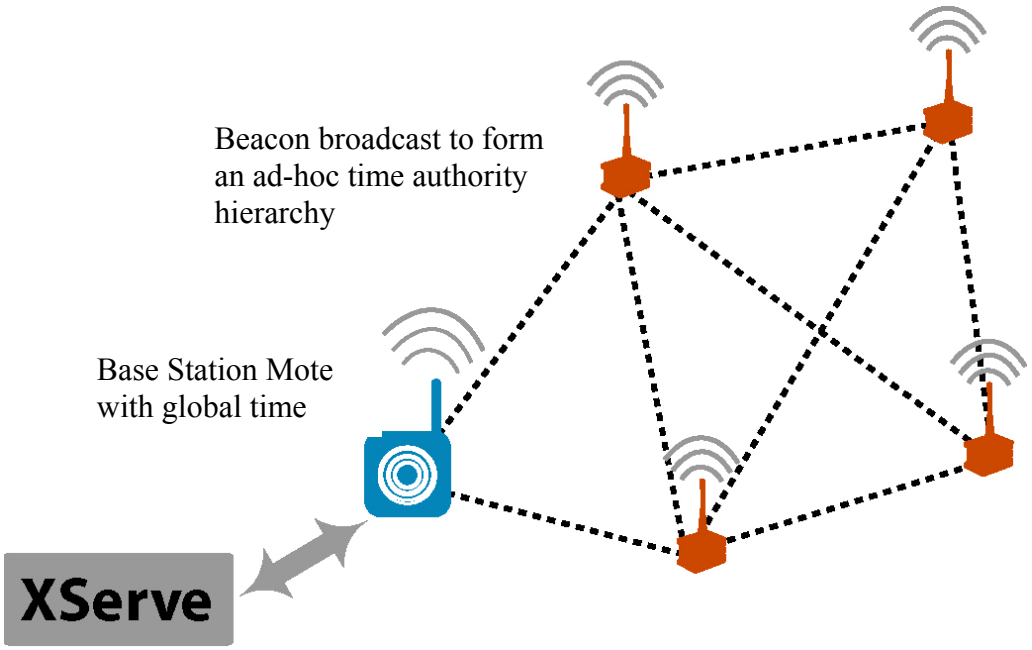


Figure 10-13. Time Synchronization in LP Network

In addition to resetting the local clock to the new value, the time synchronization method also calculates the difference between the new value and the existing clock value in order to estimate the crystal skew. The estimated crystal skew value is used to automatically update the clock in between receiving synchronization messages. The synchronization update messages are simply used to confirm that the current clock correction parameters are accurate.

The *XMesh* Time Synchronization service is available for *XMesh* networks using the Low Power (LP) mode. The purpose of the Time Synchronization is to synchronize all the nodes in the network to the same time. This is accomplished by declaring the time on the base station Mote as the global time, then synchronizing all the nodes within the *XMesh* network to the global time.

This time stamp technique achieves a time synchronization of all the nodes in the *XMesh* network with ±1 msec error.

10.5.1 Calculating Offset and Skew

It is often not sufficient to just periodically update the time of all nodes in a network. Crystals used to keep track of time at different nodes are slightly different. Typical accuracy of a mote clock crystal is around 20 to 30 ppm. That means that for a 32 kHz clock crystal, the time will drift more that 1 msec apart from the global time in only 30 second after an update. Thus it is important to also track the rate of the local crystal to the rate of the global time scale.

The ratio of the rate of the global time over the rate of the local time is called the Skew and the difference between the global time and the local time is called the offset. One common equation that expresses the local time in terms of the global time is

$$C_i(t) = a_i t + b_i$$

where t is the global time, a_i is the skew and b_i is the offset. By keeping track of the skew, it is possible to keep desired synchronization with fewer time updates.

To obtain the current global time from the *XMesh* Time Synchronization service, your applications must be wired to the `TimeSyncService` module using the `Time` interface.

The `Time` interface provides the following commands:

```
interface Time {
  /**
   * get current time. Return it in tos_time_t structure
   **/
  async command tos_time_t get();

  /** get the high 32 bits of current time */
  async command uint32_t getHigh32();

  /** get the lower 32 bits of current time */
  async command uint32_t getLow32();

  /** get clock phase offset since last clock tick
    * in unit of micro-seconds.
   **/
  async command uint16_t getUs();
}
```

Here is the `tos_time_t` structure:

```
typedef struct {
    uint32_t high32;
    uint32_t low32;
}tos_time_t;
```

☑ EXAMPLE

Below is a wiring example to the `TimeSyncService`:

```
uses {
    interface StdControl as TimeStart;
    interface Time;
  }
…
implementation{
  components YourAppM, TimeSyncService;
  YourApp.TimeStart -> TimeSyncService;
  YourApp.Time -> TimeSyncService;
…
}
```

Time is represented by the `tos_time_t` structure. The `tos_time_t` is a 64-bit integer which represents the current time as a number of milliseconds. The 64-bit integer is represented as two 32-bit integers for easier access on platforms which do not recognize 64-bit numbers. The high 32 bits are the most significant bits in the 64 bit time and the low32 bits are the least significant 32 bits in the 64-bit time. The structure of the time packet is provided in Table 10-5. Time Synchronization Packets use AM type 239 and do not use a mutihop header.

Table 10-5. Time Packet Structure

Parameter	Format	Description
`source_addr`	`uint16_t`	Source address of time message
`phase`	`uint8_t`	The difference between the mote's local time and the time update from the last timesync message.
`corr`	`uint8_t`	Smoothed out skew correction value
`authority`	`uint8_t`	Authority is the mechanism to form a timesync hierarchy. Each node's initial authority is its local address (with base station being 0). After that, each node only accepts timesync packets from nodes with a lower authority. Once a time sync packet is accepted the nodes local authority becomes the authority of its timesync parent + 2. Every timesync period the nodes authority increments by one. This is so nodes that lose their timesync parent will eventually be able to attach to another node since it will be increasing authority every period.
`timeH`	`uint32_t`	Most significant 32 bits
`timeL`	`uint32_t`	Least significant 32 bits (lsb = 1000/1024 sec)

11 XSniffer

Crossbow has developed a tool, *XSniffer*, which allows users to monitor multi-hop communication over XMesh. This program runs on a PC and uses a MICA2 or MICAz Mote to monitor the RF packet traffic. There are two applications to support *XSniffer*:

1. *XSniffer* TinyOS code: This code can be built for either a MICA2 or MICAz that runs on a Crossbow MIB510 or MIB520 base station. The source code is located in ***/MoteWorks/apps/general/XSniffer***.
2. *XSniffer* GUI which installs and runs on the PC. The executables are installed in `C:\Program Files\Crossbow\Sniffer`.

◂ **NOTE:** *XSniffer* is set for a group ID=0 and TOS_LOCAL_ADDRESS = 0xff00 so that it should never return an acknowledgement for any radio packet meant for another Mote.

11.1 Building and Starting XSniffer

In the ***/MoteWorks/apps/general*** directory, build and install the application for the correct platform. For a MICAz and a MIB510 this would be

```
make install micaz mib510,/dev/ttyS0
```

⚠ **WARNING:** *XSniffer* does not run *XMesh*, do not use route,hp or route,lp variables when building. *XSniffer* uses `TOSH_DATA_LENGTH` = 64 which should accommodate the largest user data packets.

Start the *XSniffer* GUI, select the correct COM port and START. Network messages should start to appear in the Log tab.

11.2 Using XSniffer

XSniffer can be used to monitor the behavior of the mesh. It will display all radio messages overhead within its radio range. Users can use *XSniffer* to:

- Check to see if a mote has joined the mesh. When this happens the health and data packets will change from a broadcast address to either the base station address or the address of another parent.
- Monitor the packet sequence numbers of individual mote radio packets.
- Monitor downstream radio communication from the base station.
- Monitor radio message retries.
- Monitor route update and time synchronization messages.

⚠ **WARNING:** *XSniffer* can only hear radio messages within its radio range. Normally the *XSniffer* Mote is located near the base station so that it can monitor all upstream and downstream traffic from the base station. In this position it will only overhear Route Update Messages from nearby neighbors within one hop.

11.2.1 Options Tab

This page allows users to control *XSniffer* and set display filters for incoming messages:

Table 11-1. *XSniffer* Options

Column	Description
Use Filter	Allows users to set filters on incoming messages based on the message parameters and using AND/OR logic
Packet Types	XMesh: Display incoming packets as XMesh multihop.
	General: Display incoming packets as general TOS packets
RSSI Display	Display the RF strength either as an ICON or decimal value
Log File Options	Log incoming messages to a file
Log Numeric Format Option	Log incoming data in selected format
Packet Detection Efficiency	Measures the percent of packets received over the last n seconds.
Time Sync	Computes the time skew of the global time stamp between the selected mote (usually the base station) and the displayed motes (TimeSync tab)
Special Packets	Allows users to display special packet types in the Log screen by editing the XSniffer configuration file.

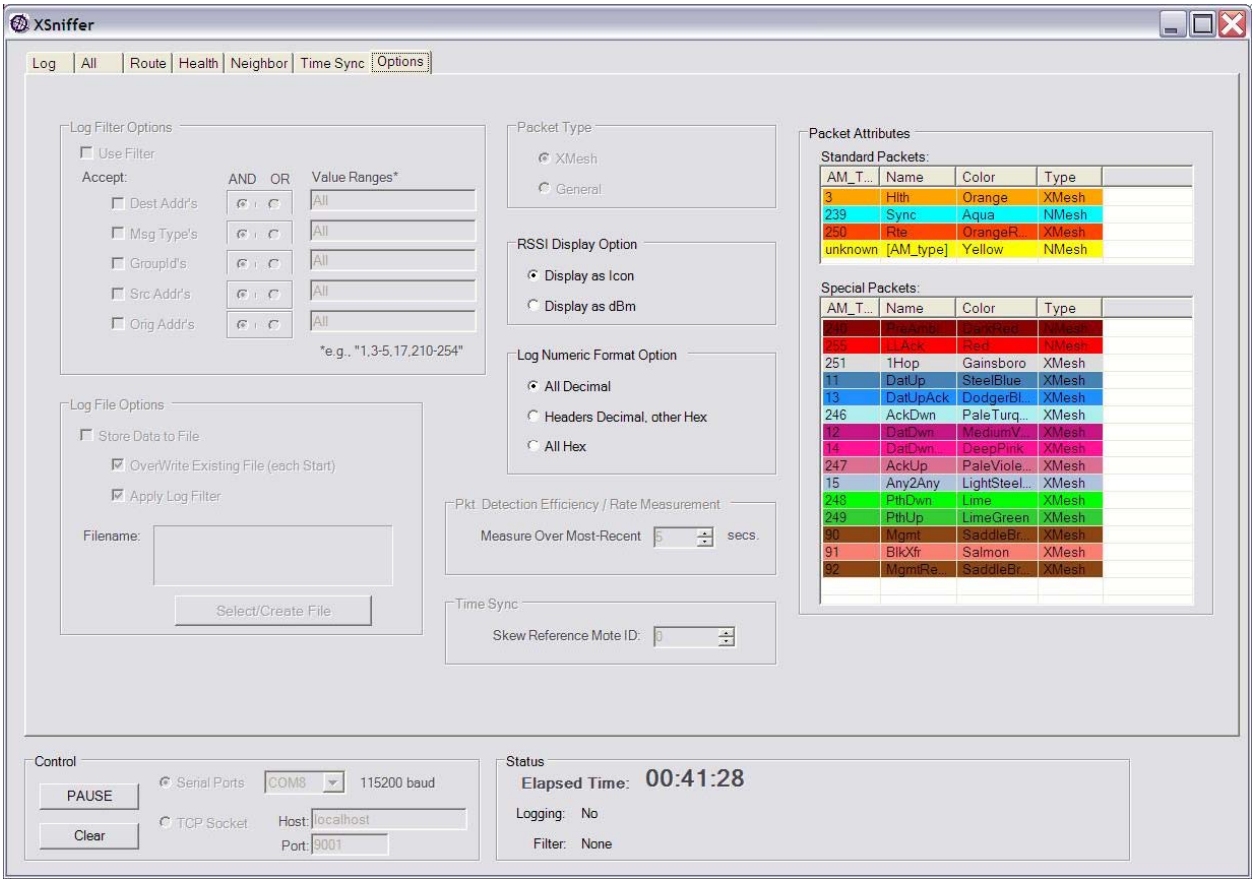


Figure 11-1. *XSniffer* GUI Options Screen Display

11.2.2 Log Screen

This screen displays all radio traffic allowed by the filter (see options tab).

Table 11-2. *XSniffer* Log Screen Parameters

Column	Description		
Elapsed time	Timestamp of the message, stamped by the PC		
Addr	The destination address of the message	Bcast	Local broadcast message
		Base	Upstream message to base
		Others	Id of the receiving mote
RF	Either numerical or icon display of the radio receive strength (RSSI) as measured by the XSniffer mote radio.		
Type	AM message type	Rte	Route Update
		Hlth	Health Message
		Sync	Global Time Sync
		E2EAck	End to End Ack
Grp	Group ID		
Len	Length of message		
Src	Address of mote that sent the message		
Orgn	Address of mote the originated the message		
SeqNo	Sequence number of the message. This number is incremented by the Src mote each time it transmits a new message (for multihop messages only)		
Hops	This field contains hop_count for route update message(Rte), it contains application id for any other message.		
AppId	Application ID		
Remaining columns	Data content of message		

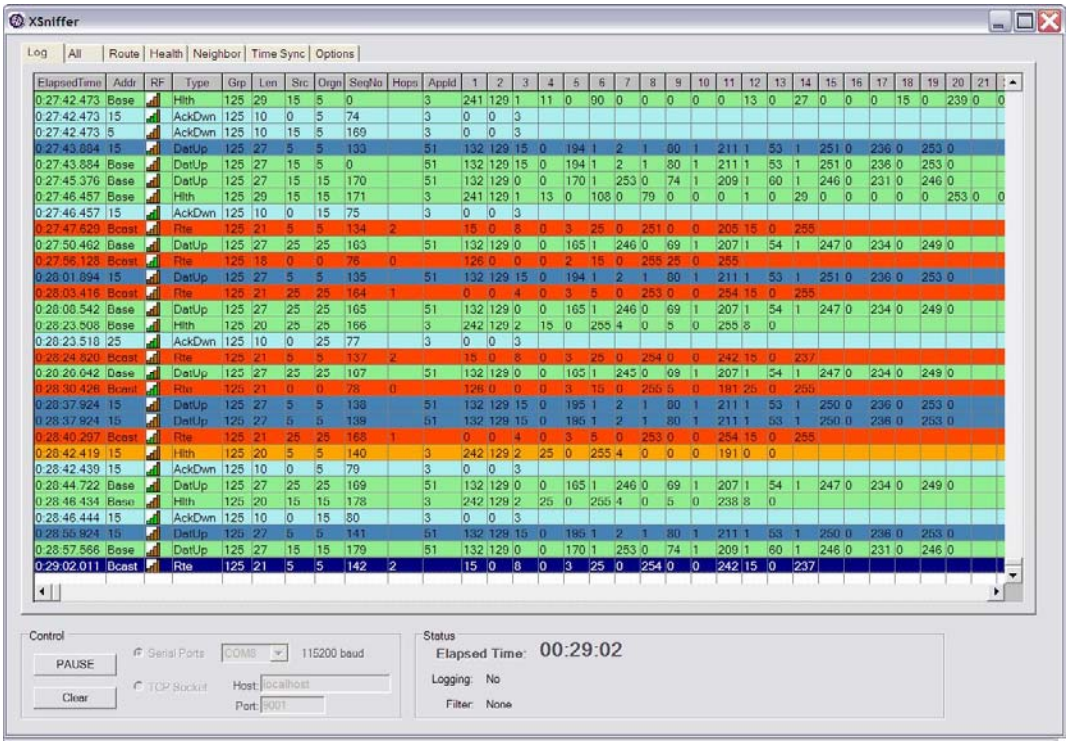


Figure 11-2. *XSniffer* Log Screen Display

11.2.3 All

Display a summary of all received messages

Table 11-7. *XSniffer* All Tab Parameters

Column	Description
Id	Id of the sending mote
Gr	The group number
Route Msg#	Number of route update messages detected.
Time	Time since last message heard (sec)
Health Msg#	Number of health messages detected
Time	Time since last message heard (sec)
Data Msg#	Number of data messages detected
Time	Time since last message heard (sec)
TimeSync Mst#	Number of time sync messages detected
Time	Time since last message heard (sec)

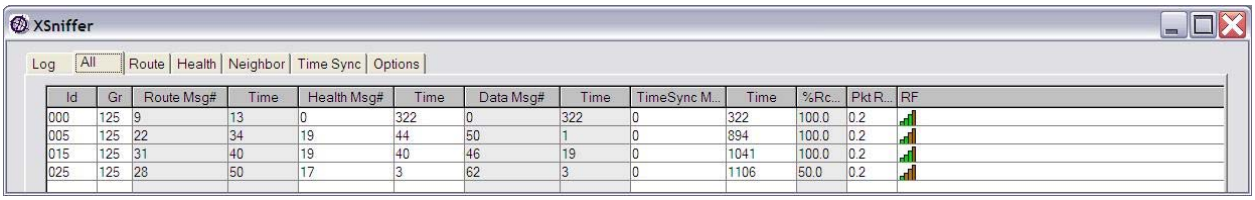


Figure 11-7. *XSniffer* All Screen Display

11.2.4 Route

This tab displays the route messages. Since this is only a local broadcast message (not forwarded to the base) not all messages will be detected by *XSniffer*. The tab displays the normal multihop information.

Table 11-3. *XSniffer* Route Parameters

Column	Description
Id	Id of the reporting node
Seq#	Sequence number of the message
Hops	How many hops away the node is from the base station
Parent	Parent of the node
Cost	Cost of sending a message to the base station
Entries	Number of neighbors carried in this message
Idx	Id of the neighbor
Estx	send estimate for the neighbor
Msg#	Number of message received from this node
Time	How long ago (in second) the last message was received

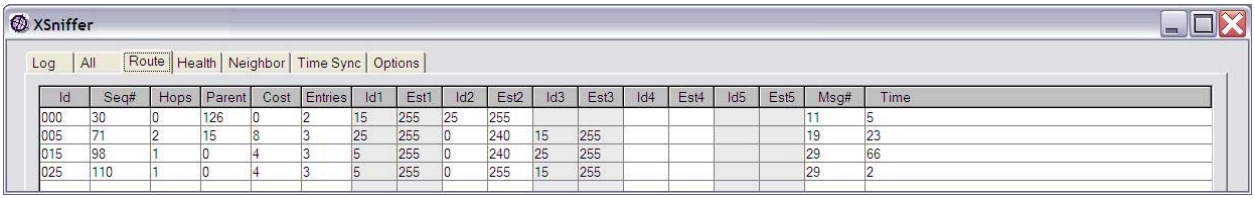


Figure 11-3. *XSniffer* Route Screen Display

11.2.5 Health

This tab displays health messages.

Table 11-4. *XSniffer* Health Tab Parameters

Column	Description
Id	Address of mote originating the health packet
MSeq#	Sequence number of the health packet. This is not the multihop header sequence number. Each health packet from a mote has it's own incrementing sequence number
Pwr	XMesh power state (LP or HP)
Vers	Version of XMesh application
HSeq#	Sequence number of the health packet
App#	Number of packets generated by the Mote
Fwd#	Number of packets forwarded by the Mote
Drop#	Number of packets dropped by the Mote
ReXmit#	Number of packets re-transmitted by the Mote
Volts	Battery voltage reported by the Mote
RF	The radio strength of the parent as heard by the mote originating the health packet.
Rsvd	Reserved for internal use
Parent	Parent of the node
LQ	Link quality of neighbor (send estimate and receive estimate). A value of 100 means 100% of messages have been heard/received
CostEst	Cost of sending a message to the base station
Msg#	Number of messages overheard by XSniffer since the start of the test
Time	Time since last message was heard (seconds)

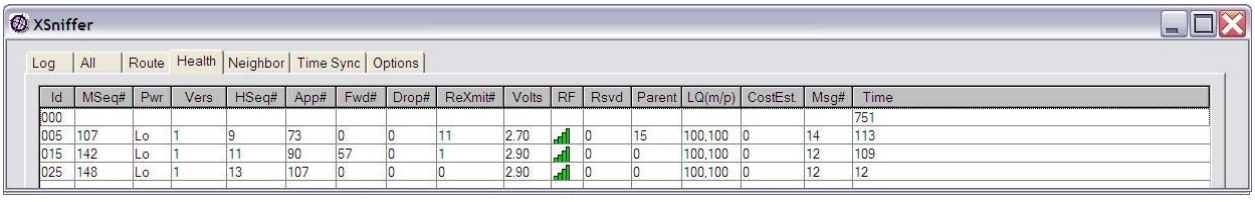

XSniffer
Log
All
Route
Health
Neighbor
Time Sync
Options
Id MSeq# Pwr Vers HSeq# App# Fwd# Drop# ReXmit# Volts RF Rsvd Parent LQ(m/p) CostEst Msg# Time
000 751
005 107 Lo 1 9 73 0 0 11 2.70 0 15 100,100 0 14 113
015 142 Lo 1 11 90 57 0 1 2.90 0 0 100,100 0 12 109
025 148 Lo 1 13 107 0 0 0 2.90 0 0 100,100 0 12 12

Figure 11-4. *XSniffer* Health Screen Display

11.2.6 Neighbor

The neighborhood display is based on information derived from health packets and gives information as to the quality of the radio links to nearby neighbors.

Table 11-5. *XSniffer* Neighborhood Tab Parameters

Column	Description
Id	Address of mote originating the health packet
MSeq#	Sequence number of the health packet. This is not the multihop header sequence number. Each health packet from a mote has it's own incrementing sequence number
Msg#	Number of messages overheard by XSniffer since the start of the test
Time	Time since last message was heard (seconds)
Cnt	Number of neighbors contained in this packet.
nbrID	Neighbor address
LQ	Link quality of neighbor (send estimate and receive estimate). A value of 100 means 100% of messages have been heard/received
Hops	Hop count of neighbor to base station
RF	The radio strength of the parent as heard by the mote originating the health packet.

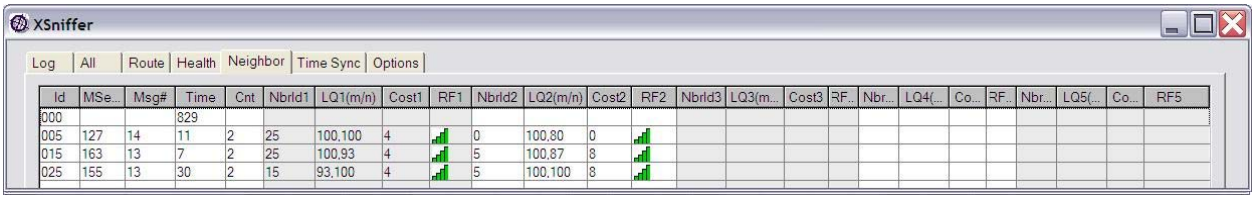


Figure 11-5. *XSniffer* Neighbor Screen Display

11.2.7 TimeSync

This tab displays time synchronization messages.

Table 11-6. *XSniffer* TimeSync Tab Parameters

Column	Description
Id	Id of the sending mote
Phase	Sequence Number of the message, obtained from the Multihop header
Corr	See section 10.4
Authority	See section 10.4
Raw Time	See section 10.4
Elapsed Time	Global time as referred to the base station (see Options Tab)
Skew (msec)	The time difference between the time message and the base station time. This computation is based on when the PC time stamps the incoming message. Due to variable time delays in the sniffer and serial port communication this computation is only roughly accurate (~100 msec).
Msg#	Number of time sync messages detected
Time	How long ago (in second) the last message was received

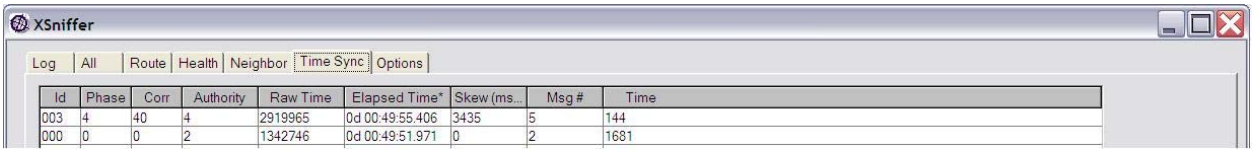


Figure 11-6. *XSniffer* TimeSync Screen Display

12 MoteConfig

MoteConfig is a GUI utility for programming Motes. It provides an interface for downloading pre-compiled TinyOS software applications. A major benefit of *MoteConfig* is that Mote platforms can be programmed without having to install the TinyOS programming environment.

1. MoteConfig dialog window can be started from *MoteView* by clicking on **Tools > Program Mote...** or by double-clicking icon on your Desktop. This will bring up a window shown in Figure 12-1. Click **Local Program** on tab.

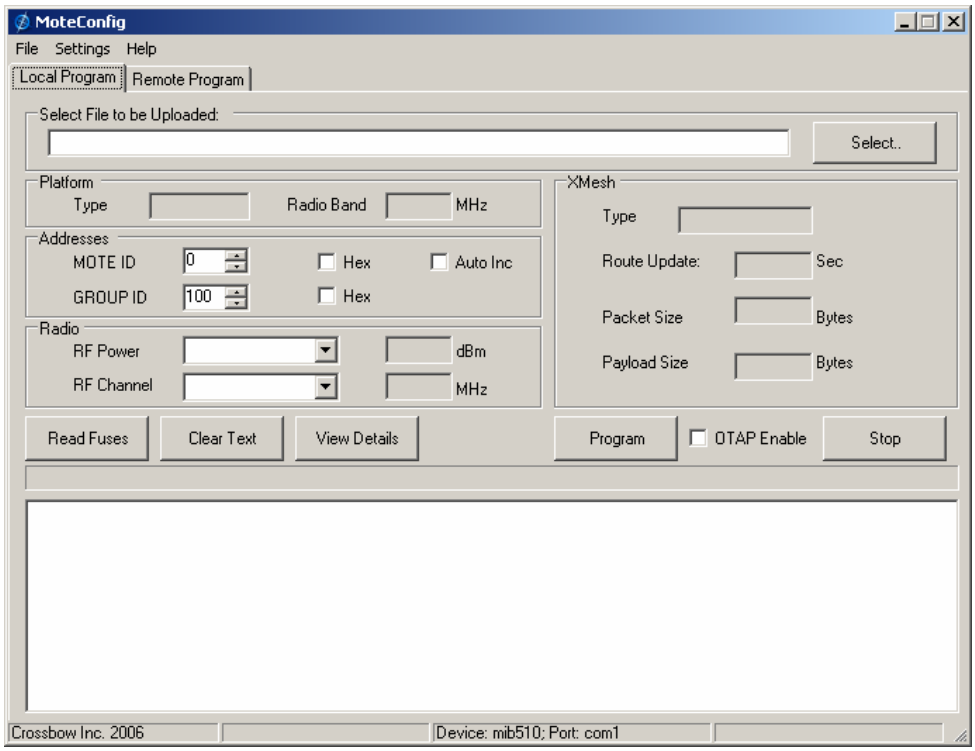
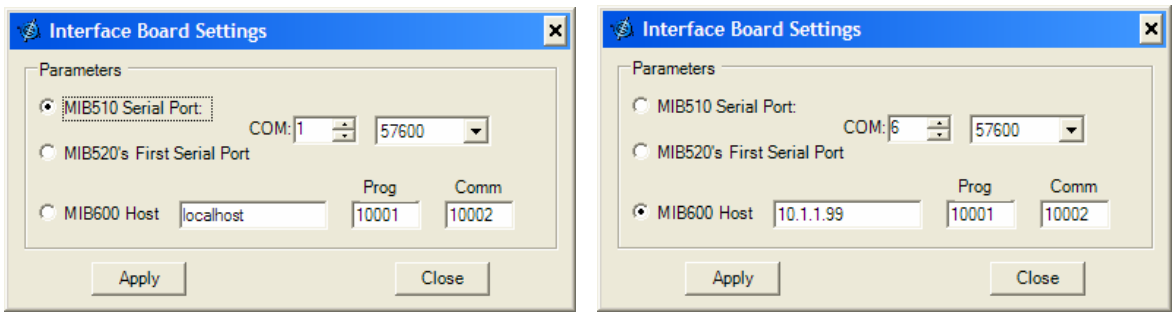


Figure 12-1. Screenshot of MoteConfig GUI Window

2. Click on **Settings > Interface Board Settings...** and choose the proper MIB gateway and check that the port settings are correct.

☑ **EXAMPLE 5-1:** Left screenshot shows **Interface Board Settings** for an MIB510 on COM port 1. Right screenshot shows **Interface Board Settings** for an MIB600 with IP address 10.1.1.248 and on the same LAN as that of the PC.



3. Right click on the **Select...** button on the top right which will open up a directory window (see Figure 12-2 or navigate to another directory which has the pre-compiled Mote application you wish to install. Select the specific **.exe** file of the application you want to download into the Mote.

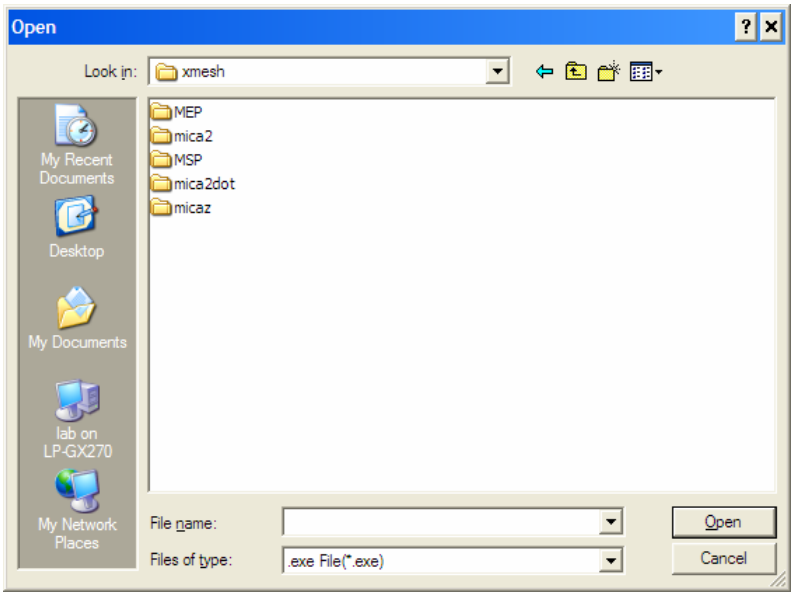


Figure 12-2. Screenshot for selecting XMesh applications

NOTE: The XMesh applications distributed with MoteView now require *XMeshBase_xxx.exe* programmed with MOTE ID=0 as base station application.

The binary scan feature built into MoteConfig will display the default parameters programmed into this application.

4. Specify desired **MOTE ID, Group ID, RF Power,** and **RF Channel** from the drop down menus.
5. Right-click on the **Program** button and you will see the resulting output at the bottom of the screen (see Figure 12-3).

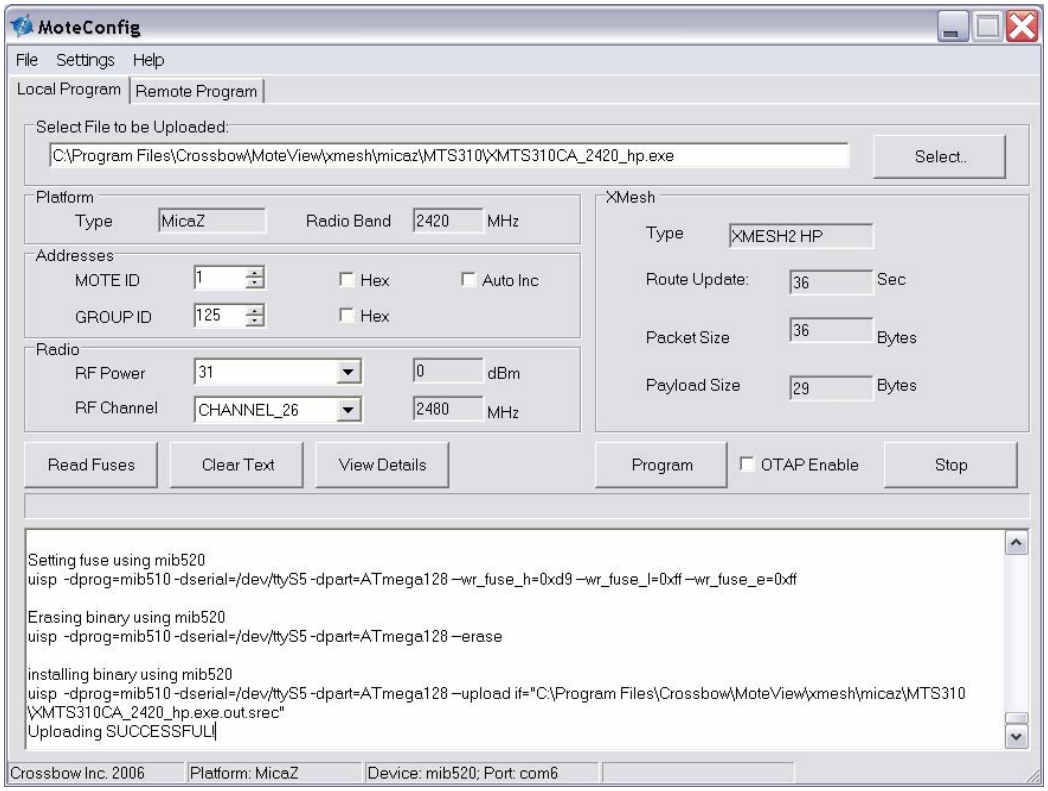


Figure 12-3. Screenshot of MoteConfig which scanned the main.exe executable file.

The *MoteConfig* displays the following information that was compiled into the application.

Table 12-7. *MoteConfig* Parameters

Display	Description	Programmable?
Platform	The type of mote.	No
XMesh Type	The XMesh configuration.	No
Packet Size	The TOS message packet size.	No
Payload Size	The payload data size within the packet.	No
App Sensor	Not used.	No
RF Power	The power output of the radio. Displayed a register value and dBm.	Yes
Radio Band	The radio frequency band.	No
Channel No	The radio channel within the radio band.	Yes
UART0 baud	The baud rate for UART0 on the mote	Yes
Mote Id	The mote address to program into the unit. This address can be auto-incremented after each unit is programmed.	Yes
Group Id	The group id of the network	Yes
Health Update	The update rate (sec) of health packets	Yes
Route Update	The route update rate (note: all motes must have the same route update rate)	Yes

MoteConfig also allows users to load an OTAP image into the serial flash memory (see Section 10.2). The **Enable Watch Dog** checkbox will enable a watchdog timer (see Appendix A).

13 Appendix A: XMesh Constants

The following constants (#defines) in the *XMesh* code are used to set configuration parameters that affect the performance of *XMesh*.

Parameter	Default Value	Description
TOSH_DATA_LENGTH	29	Defines the maximum data for a tos packet. **If changed, make sure that *XMeshBase* uses equal or greater value.**
BASE_STATION_ADDRESS	0	Mote address of base station. Should never be changed
ROUTE_UPDATE_INTERVAL	60 sec for HP 600 sec for LP	Time between route update intervals. These values should not be changed. **If changed, make sure that *XMeshBase* and the application use the same values.**
HEALTH_UPDATE_INTERVAL	60	Time between health messages (seconds)
ROUTE_TABLE_SIZE	Base: 30 Others: 15	Defines maximum number of neighbors that mote can track. If a mote is not in this table it will not be selected as a parent.
DESCENDANT_TABLE_SIZE	Base: 100 Others 50	Defines the maximum number of children for the mote. Used for downstream communication
MHOP_QUEUE_SIZE	Base: 16 Others: 8	Define the maximum number of multihop messages the mote can queue up. Once exceeded messages will be dropped.
USE_WATCHDOG	0	Enables reboot if no route update messages are heard within a defined interval
FEATURE_HEARTBEAT	0	Enable/disable base station heartbeat

Mote Addresses

Parameter	Values	Description
BASE_STATION_ADDRESS	0x0	Base station address
TOS_LOCAL_ADDRESS	n/a	Mote address, usually assigned when loading code (via install.x or reinstall.x or MoteConfig)
TOS_BCAST_ADDR	0xffff	Broadcast address; radio messages addressed to this address can be received by all motes
TOS_UART_ADDR	0x007e	TOS messages with this address are sent to the uart port.

Platform Defines

(set when building for a specific platform)

Define	Description
TOSH_HARDWARE_MICAZ	Code is built for MICAz
TOSH_HARDWARE_MICA2	Code is built for MICA2

TOSH_HARDWARE_MICAZC	Code is built for IRIS

Application IDs

Parameter	Values	Description
Application ID	1-127	User available
Application ID	128-255	Crossbow reserved

AM Messages Types

User applications only deal with Application ID through using the MhopSend/receive interface to send/receive message, and *XMesh* decides which AM type is appropriate for that message. AM type is internal to *XMesh*; currently there are 20 predefined AM type in *XMesh* that users should never use for other purposes. The most current values can be found in the *message.h* file. The following table shows some of the presently used values.

Name of AM Type (#Define)	Value of AM_Type	Description
AM_HEALTH	3	Reserved for Health packets from the mote
AM_DATA2BASE	11	Upstream data msg from node to base, no end-end ack
AM_DATA2NODE	12	Downstream data to node
AM_DATAACK2BASE	13	Upstream guaranteed delivery to base
AM_DATAACK2NODE	14	Downstream guaranteed delivery to node
AM_ANY2ANY	15	Any to any
AM_MGMT	90	OTAP status message
AM_BULKXFER	91	OTAP transfer fragment
AM_MGMTRESP	92	OTAP status acknowledgement
AM_TIMESYNC	239	Time Sync packet
AM_PREAMBLE	240	Low power preamble packet
AM_FASTJOIN	241	Fast join
AM_FASTJOINRESP	242	Fast join
AM_DOWNSTREAM_ACK	246	Ack message from base to node
AM_UPSTREAM_ACK	247	Ack message from node to base
AM_PATH_LIGHT_DOWN	248	Light full power path down to node
AM_PATH_LIGHT_UP	249	Light full power path up to base
AM_MULTIHOPMSG	250	Route update message

Name of AM Type (#Define)	Value of AM_Type	Description
MODE_ONE_HOP_BROADCAST	251	Single-hop service via XMesh
AM_HEARTBEAT	253	Base station heart beat message

⚠ **WARNING:** Do not use the AM parameter in multihop message when sending messages; this parameter is reserved by *XMesh*.

14 Appendix B: MICA FUSE SETTINGS

The ATmega128L and ATmega1281 microprocessors used on all MICA Motes have multiple fuses that control their operation. These CPU's fuses can be set with UISP when downloading code to the mote. The UISP allows users to individually set the high and low byte fuse. The following tables from the ATmega128L and ATmega1281 manuals show these fuse settings.

The following table corresponds to bit settings in the `uisp wr_fuse_h` setting for ATmega128L:

Fuse High Byte	Bit No.	Description	Default Value
OCDEN	7	Enable OCD	1 (unprogrammed, OCD disabled)
JTAGEN	6	Enable JTAG	0 (programmed, JTAG enabled)
SPIEN	5	Enable Serial Program and Data Downloading	0 (programmed, SPI prog. enabled)
CKOPT	4	Oscillator options	1 (unprogrammed)
EESAVE	3	EEPROM memory is preserved through the Chip Erase	1 (unprogrammed, EEPROM not preserved)
BOOTSZ1	2	Select Boot Size	0 (programmed)
BOOTSZ0	1	Select Boot Size (see Table 112 for details)	0 (programmed)
BOOTRST	0	Select Reset Vector	1 (unprogrammed)

The following table corresponds to bit settings in the `uisp wr_fuse_h` setting for ATmega1281:

Fuse High Byte	Bit No.	Description	Default Value
OCDEN	7	Enable OCD	1 (unprogrammed, OCD disabled)
JTAGEN	6	Enable JTAG	0 (programmed, JTAG enabled)
SPIEN	5	Enable Serial Program and Data Downloading	0 (programmed, SPI prog. enabled)
WDTON	4	Watchdog Timer always on	1 (unprogrammed)
EESAVE	3	EEPROM memory is preserved through the Chip Erase	1 (unprogrammed, EEPROM not preserved)
BOOTSZ1	2	Select Boot Size	0 (programmed)
BOOTSZ0	1	Select Boot Size (see Table 112 for details)	0 (programmed)
BOOTRST	0	Select Reset Vector	1 (unprogrammed)

The following table corresponds to bit settings in the uisp wr_fuse_l setting for ATmega128L:

Fuse Low Byte	Bit No.	Description	Default Value
BODLEVEL	7	Brown out detector trigger level	1 (unprogrammed)
BODEN	6	Brown out detector enable	1 (unprogrammed, BOD disabled)
SUT1	5	Select start-up time	1 (unprogrammed)
SUT0	4	Select start-up time	0 (programmed)
CKSEL3	3	Select Clock source	0 (programmed)
CKSEL2	2	Select Clock source	0 (programmed)
CKSEL1	1	Select Clock source	0 (programmed)
CKSEL0	0	Select Clock source	1 (unprogrammed)

The following table corresponds to bit settings in the uisp wr_fuse_l setting for ATmega1281:

Fuse Low Byte	Bit No.	Description	Default Value
CKDIV8	7	Divide clock by 8	0 (programmed)
CKOUT	6	Clock output	1 (unprogrammed)
SUT1	5	Select start-up time	1 (unprogrammed)
SUT0	4	Select start-up time	0 (programmed)
CKSEL3	3	Select Clock source	0 (programmed)
CKSEL2	2	Select Clock source	0 (programmed)
CKSEL1	1	Select Clock source	1 (unprogrammed)
CKSEL0	0	Select Clock source	0 (programmed)

The following table corresponds to bit settings in the uisp wr_fuse_e setting for ATmega128L:

Extended Fuse Byte	Bit No.	Description	Default Value
–	7	–	1
–	6	–	1
–	5	–	1
–	4	–	1
–	3	–	1
–	2	–	1
M103C(1)	1	ATmega103 compatibility mode	0 (programmed)
WDTON(2)	0	Watchdog Timer always on	1 (unprogrammed)

The following table corresponds to bit settings in the uisp wr_fuse_e setting for ATmega1281:

Extended Fuse Byte	Bit No.	Description	Default Value
–	7	–	1
–	6	–	1
–	5	–	1
–	4	–	1
–	3	–	1
BODLEVWL2(1)	2	Brown-out Detector trigger level	1 (unprogrammed)
BODLEVWL1(1)	1	Brown-out Detector trigger level	1 (unprogrammed)
BODLEVWL0(1)	0	Brown-out Detector trigger level	1 (unprogrammed)

⚠ **WARNING:** The base station mote (mote id = 0) must run with the **external** clock enabled otherwise the UART baud rates will not be correct.

Do not run a MICA2DOT as a base station mote. It uses a 4MHz resonator crystal which is not accurate enough for high speed uart baud rates.

Always program a MICA2DOT using the internal, 8MHz, oscillator.

The fuse settings can be set via a uisp command such as:

```
uisp -dprog=mib510 -dserial=/dev/ttyS0 --wr_fuse_h=0xd8 -dpart=ATmega128 -
-wr_fuse_e=ff
```

There are several fuses that must be set for correct XMesh operation:

The following table shows fuse setting for ATmega128L:

XMesh configuration	wr_fuse_h	wr_fuse_l	wr_fuse_e	Description
XMesh-LP and XMesh-ELP (no OTAP)	0xd9	0xc4	0xff	• Clock Source: Internal Oscillator • Brown out detect: disabled • JTAG: disabled • BootLoader: disabled
XMesh-LP and XMesh-ELP (OTAP)	0xd8	0xc4	0xff	• Clock Source: Internal Oscillator • Brown out detect: disabled • JTAG: disabled • BootLoader: enabled
XMesh-HP (OTAP)	0xd8	0xff	0xff	• Clock Source: Internal oscillator • Brown out detect: disabled • JTAG: disabled • BootLoader: enabled
Base Station (XMeshBase)	0xd9	0xbf	0xff	• Clock Source: External oscillator • Brown out detect: enabled • JTAG: disabled • BootLoader: disabled

The following table shows fuse setting for ATmega1281:

XMesh configuration	wr_fuse_h	wr_fuse_l	wr_fuse_e	Description
XMesh-LP and XMesh-ELP (no OTAP)	0xd9	0xc2	0xff	• Clock Source: Internal Oscillator • Brown out detect: disabled • JTAG: disabled • BootLoader: disabled
XMesh-LP and XMesh-ELP (OTAP)	0xd8	0xc2	0xff	• Clock Source: Internal Oscillator • Brown out detect: disabled • JTAG: disabled • BootLoader: enabled
XMesh-HP (OTAP)	0xd8	0xff	0xff	• Clock Source: Internal oscillator • Brown out detect: disabled • JTAG: disabled • BootLoader: enabled
Base Station (XMeshBase)	0xd9	0xff	0xfd	• Clock Source: External oscillator • Brown out detect: enabled • JTAG: disabled • BootLoader: disabled

NOTE: Enabling the JTAG fuse allows users to debug code on the ATmega128 using a JTAG pod. If this fuse is enabled on motes running *XMesh-LP/ELP* then the power consumption will increase.

Using the internal 8MHz oscillator reduces power consumption. The only time the external oscillator is needed is for the base station Mote.

Setting fuses with the fuses script

The ***/MoteWorks/tools/bin*** has a script which allows the fuses to be read and written easily. The screen shot below shows the options. The fuses script can be invoked from any application directory by setting an alias in the profile file (see Appendix C).

```
$ fuses
fuses Ver:$Id: fuses,v 1.1 2005/03/01 17:24:19 jprabhu Exp $
  Usage: fuses [command] [port] [args]
    read     = read fuses
    clkint   = set to internal oscillator
    clkext   = set to external oscillator
    jtagen   = enable JTAG
    jtagdis  = disable JTAG

 Command  Flag
 -------  ------------------------------------------------------------
  clkext  --wr_fuse_l=0xff
  clkint  --wr_fuse_l=0xc4
 jtagdis  --wr_fuse_h=0xd9
  jtagen  --wr_fuse_h=0x19
    read  --rd_fuses
```

15 Appendix C: TinyOS Settings and Scripts

When building TinyOS applications for *XMesh* make sure the environment variables are set correctly. If the installation was at ***/opt/MoteWorks***, do the following at the Cygwin command line.

```
export TOSROOT=/opt/MoteWorks
export TOSDIR=/opt/MoteWorks/tos
export MAKERULES = /opt/MoteWorks/make/Makerules
```

These environment variables can be checked by entering:

```
echo $TOSROOT
echo $TOSDIR
ehco $MAKERULES
```

Note these variables can be automatically set in the opt/etc/profile file by entering:

```
#set TOS variables
export TOSROOT=/opt/MoteWorks
export TOSDIR=/opt/MoteWorks/tos
export MAKERULES=/opt/MoteWorks/Makerules
```

Cygwin Profile File

The profile file is executed when Cygwin starts up and is useful for executing scripts that set paths and other variables. This file is usually contained in ***MoteWorks Suite/cygwin/etc***.

- To set a path to the fuses script (see previous appendix) from any application directory

  ```
  alias fuses="/opt/Moteworks/tools/bin/fuses"
  ```

- To set the serial port as COM1

  ```
  export AVRICE_ARGS="-j /dev/ttyS0"
  ```

- To invoke the avr-ice jtag program for a MICAz:

  ```
  alias jtagmicaz="ice-insight build/micaz/main.exe"
  ```

usr/local/bin File

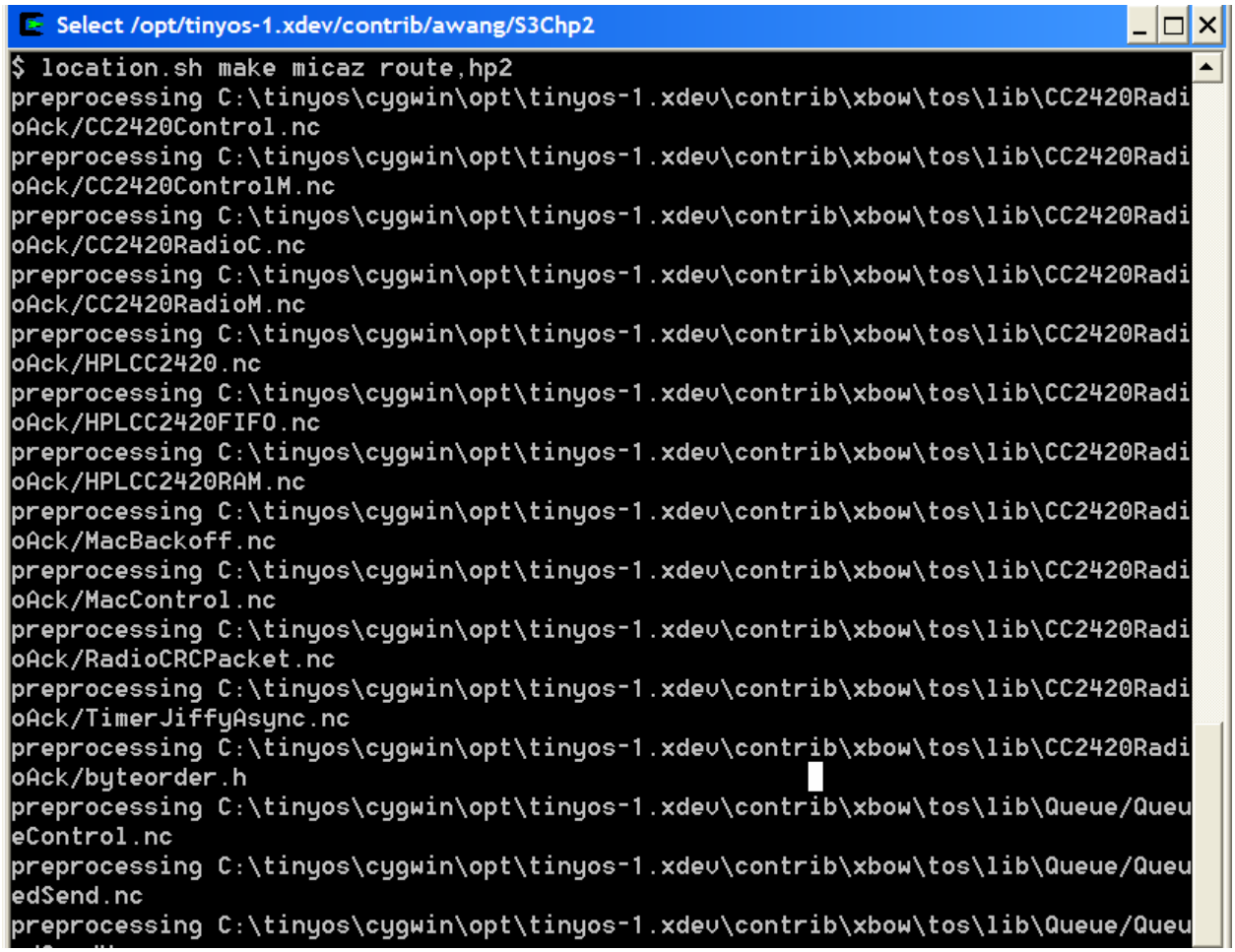
Scripts can be executed directly if they're located in ***MoteWorks Suite/cygwin/usr/local/bin***. Several scripts such as *location.sh*, *fuses*, *gettos*, *settos* (located in ***/MoteWorks/tools/bin***) can be copied to the usr/bin file.

TinyOS scripts

location.sh: This script will list all the files compiled into the application. Run this script only after successfully building an application. For example

```
location.sh make micaz route,hp
```

will show an output similar to:



16 Appendix D: TinyOS Components

Some commonly used TinyOS components are provided below.

Component	**LedsC**
Wiring Example	`MyappM.Leds->LedsC.Leds`

Usage	`call Leds.redOn(); call Leds.redToggle();`
	`call Leds.yellowOn(); call Leds.yellowToggle();`
	`call Leds.greenOn(); call Leds.greenToggle();`

Description	Turn on/off/toggle red,yellow,green leds
Component	**NoLeds**
Wiring Example	`MyappM.Leds -> NoLeds;`
Usage Example	`call Leds.redOn(); call Leds.redToggle();`
Description	This component is any easy way to disable leds without changing any code in the application module. In the wiring file (ex Myapp.nc) do #ifdef NO_LEDS MyappM.Leds -> NoLeds; #else MyAppM.Leds -> LedsC; #endif
Component	**TimerC**
Wiring Example	`MyappM.Timer -> TimerC.Timer[unique("Timer")];` [1]
Usage Example	`call Timer.start(TIMER_REPEAT, 1000);` `call Timer.start(TIMER_ONE_SHOT,5000);`
Description	Fire a repetitive or one-shot timer. Time is set in milliseconds, uint_32. Minimum time is 3 msec
Component	**COMM**
Wiring Example	`MyappM.CommControl -> Comm;` `MyappM.SendMsg-> Comm.SendMsg[AM_TYPE]`
Usage Example	`Call SendMsg.send(TOS_UART_ADDR,MSG_LEN,msg_ptr);`
Description	Send a message over the uart or radio (do not use this for sending radio messages with XMesh)

Component	**HPLPowerManagementM (not a component)**

Wiring Example	`MyAppM.PowerManagement -> HPLPowerManageM;`
	`MyAppM.Enable -> HPLPowerManageM.Enable;`
	`MyAppM.Disable -> HPLPowerManageM.Disable;`

Usage Example	`call Enable();` `call PowerManagement.adjustPower();`
Description	If enabled, the call to adjustPower() will put the mote into a low power state when there are no more tasks on the task que.

[1] This is a parameterized interface. TinyOS automatically assigns a value to the unique ("Timer") value.

17 Appendix E: Computing TOS Packet CRC

The following code is used to compute the CRC of a data packet:

```
public static int calcByte(int crc, int b)
   {
   crc = crc ^ (int)b << 8;
   for (int i = 0; i < 8; i++)
   {
   if ((crc & 0x8000) == 0x8000)
   crc = crc << 1 ^ 0x1021;
   else
   crc = crc << 1;
   }
   return crc & 0xffff;
   }
   public static int calc(byte[] packet, int index, int count)
   {
   int crc = 0;
   int i;
   while (count > 0)
   {
   crc = calcByte(crc, packet[index++]);
   count--;
   }
   return crc;
   }
```

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